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The various air pollutants have been classified as primary or secondary pollutants. Primary pollutants are emitted directly to the environment from their source and include carbon monoxide, sulfur oxides, nitrogen oxides and primary particulates. Secondary pollutants develop from interactions of primary pollutants and include ozone, peroxyacetyl nitrate and certain aerosols. Carbon monoxide does not appear to cause decrements in submaximal exercise performance in healthy individuals; however, cardiovascularly-impaired individuals appear to be at significant risk during submaximal exercise even at low carboxyhemoglobin levels. Maximal exercise performance for healthy individuals seems to be altered by breathing carbon monoxide with the critical concentration being 4.3% carboxyhemoglobin. The threshold level of sulfur dioxide which effects submaximal exercise performance in healthy individuals is between 1.0 and 3.0 ppm while asthmatic individuals and possibly others with pulmonary hyperractivity are affected at a lower threshold concentration between 0.20 and 0.50 ppm. No studies have been reported concerning maximal exercise performance during sulfur dioxide exposure. Several studies suggest that healthy and asthmatic individuals may adapt to sulfur

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but unfortunately no research has investigated adaptation to this pollutant during physical exercise. While no studies have been reported which evaluate maximal exercise performance, nitrogen dioxide exposure does not appear to adversely affect submaximal exercise performance in healthy individuals. The physiological performance effects of breathing primary particulates have not been directly evaluated during exercise in man. Ozone exposure does not appear to limit submaximal exercise performance at light to moderate exercise intensities. At heavy exercise intensities, ozone exposure can limit performance primarily due to severe respiratory discomfort and changes in pulmonary functions. While adaptation occurs after two to five consecutive days of exposure to ozone, this adaptation could eventually be harmful because of the associated suppression of the normal defense mechanisms. Submaximal and maximal exercise performance have not been altered dramatically during peroxyacetyl nitrate exposure at the concentrations tested. The sulfate aerosols, sulfuric acid and the nitrate aerosols elicit minimal adverse effects relative to some of the other pollutants when tested singly. The various pollutants may interact in three ways: (a) additively, (b) synergistically, or (c) antagonistically. Clear distinction between additive and synergistic interactions is frequently difficult and usually involves the specific pollutant concentrations. In general, ozone in combination with nitrogen dioxide represent an additive interaction, while ozone combined with peroxyacetyl nitrate seem to suggest synergistic effects. No pollutant interactions have been reported that are antagonistic. Human performance of submaximal or maximal exercise can be expected to suffer under the combined stresses of excessive heat, humidity and poor air quality. The interactive effects of breathing cold polluted air should increase the degree of exercise-induced bronchospasm and adversely effect exercise performance in susceptible individuals. The adverse effects of certain pollutants such as carbon monoxide may be enhanced at high altitude due to a greater degree of hypoxemia.

CHAPTER 16

AIR QUALITY AND HUMAN PERFORMANCE

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OUTLINE

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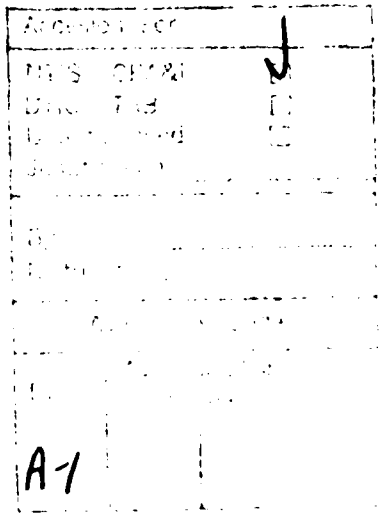

INTRODUCTION

In addition to the environmental extremes of heat, cold and altitude already discussed in this book, poor air quality or air pollution is another environmental stressor known to affect human physiological performance. The individual air pollutants have been classified as primary or secondary pollutants (81,88). Primary pollutants are those emitted directly to the environment from sources such as gasoline powered vehicles or industrial plants and exert their effects with little or no chemical change. These pollutants include carbon monoxide, sulfur oxides, nitrogen oxides, and primary particulates. Secondary pollutants are those which develop from the interaction of primary pollutants and include ozone, peroxyacetyl nitrate and certain aerosols. Four population groups have been shown to be especially susceptible to air pollution effects: asthmatics and others with respiratory disorders, athletes, children and the elderly (81,94).

Three historic air pollution episodes (the Meuse Valley, Belgium, 1930; Donora, Pennsylvania, 1948; London, 1952) and the associated medical consequences sensitized the public to the health problems of poor air quality while stimulating research leading to the development of control measures and standards. These three air pollution episodes were associated with greater than 4000 excess deaths resulting from the interactive effects of poor air quality and existing disease states such as heart and lung disorders (81,93). In part, the end result of these and other pollution episodes has led to the development of public guidelines to help assess the potential health problems associated with poor air quality as illustrated in Tables 1 and 2. Table 1 presents the possible adverse health effects of four common air pollutants (carbon monoxide, ozone, sulfur dioxide, total suspended particulates) as a function of a specific averaging time in hours and a standard described as "unhealthy". Table 2 displays the pollution

standards index (PSI) ranging from numerical values of 0 to 500 for five common pollutants (total suspended particulates, sulfur dioxide, carbon monoxide, ozone, nitrogen dioxide) and the associated health effects discriptor.

INSERT TABLES 1 and 2 ABOUT HERE

The early research studies concerning the physiological effects of the various air pollutants on man were conducted at rest while more recent research has evaluated submaximal and maximal exercise responses. The adverse physiological effects of air pollutant inhalation appear related to the intensity of exercise with generally greater adverse effects at higher intensities. The physiological effects of the various air pollutants primarily involve the respiratory tract with the site of the effect decided by the pollutants' solubility and/or size (81). The nose is very effective in removing large particulates and highly soluble gases, but is poor in the filtering of small particulates and low soluble gases. During nasal breathing, it is estimated that 99.9 percent of sulfur dioxide which is a highly-soluble gas is removed; however, oral breathing which is generally employed during exercise eliminates this major defense mechanism (81,89). Some pollutants, such as ozone which is a low soluble gas, may act at different sites along the respiratory tract. During exercise, ozone, nitrogen dioxide and sulfur dioxide generally exert their effect on the small airways and proximal alveoli resulting in alterations in mucous secretion and mucociliary clearance (44,81). Carbon monoxide penetrates to the alveoli where it binds with hemoglobin in the blood to impede oxygen transport. Thus, carbon monoxide affects exercise performance through impaired transport of oxygen in the blood while ozone, sulfur dioxide and nitrogen dioxide possibly cause an impairment in the ability to ventilate maximally (44).

INSERT FIGURE 1 ABOUT HERE

Pulmonary function tests have been used over the years to evaluate the effects of the various air pollutants. These tests can be divided into five categories: (a) lung volume measurements, (b) lung capacity measurements, (c) forced spirometry measurements, (d) airway resistance measurements and (e) measurements of pulmonary diffusing capacity (81). Several of these measurements are illustrated schematically in Figure 1.

There are four static measurements of lung volume which are performed with a spirometer (21,116). Tidal Volume (TV) is the volume of air inhaled or exhaled during each breathing cycle. Inspiratory Reserve Volume (IRV) is the maximum amount of air that can be inhaled after a normal inhalation. Expiratory Reserve Volume (ERV) is the maximum amount of air that can be exhaled after a normal exhalation. Residual Volume (RV) is the volume of air left in the lungs after a maximal exhalation.

There are four static lung capacity measurements (21,116). Total Lung Capacity (TLC) is the amount of air in the lungs after a maximal inhalation. Vital Capacity (VC) is the maximum volume of air that can be expelled from the lungs through a forceful effort after a maximal inhalation. Inspiratory Capacity (IC) is the maximal volume of air that can be inhaled from the resting expiratory level. Functional Residual Capacity (FRC) is the volume of air left in the lungs at the resting expiratory level.

Three forced expiratory measurements have been used to evaluate the effects of the various air pollutants (81). Forced Expiratory Volume (FEV_t) measures the volume of air exhaled by a maximal effort at a specific time. In practice, this measurement is made during the first ($FEV_{1.0}$) or third ($FEV_{3.0}$) second. In some instances, FEV_t is expressed as a percentage of the forced vital capacity (FVC) as $FEV_{1.0}/FVC\%$ or $FEV_{3.0}/FVC\%$. Forced Midexpiratory Flow (FEF) measures the average rate of airflow over the middle half of the FVC or $FEF_{25\%-75\%}$. Maximal Voluntary Ventilation (MVV) is the maximum volume of air that can be breathed per minute through

voluntary effort after a 12-second period when the individual is instructed to breath as hard and fast as possible.

Three airway resistance measurements are commonly used (81.116). Airway Resistance (R_{aw}) represents the difference between the alveolar and mouth pressures divided by the flow rate. Static and Dynamic Lung Compliance (C_{st}, C_{dyn}) are measurements of the detensibility of "elastic resistance" of the lungs (21). Closing Volume (CV) evaluates the distribution of an inspired gas (single breath of nitrogen) on the alveoli and is thought to be sensitive to alterations in the small airways.

The Diffusing Capacity of the lung (D_L) is a measure of the lung's ability to move a gas from the alveoli to the capillary blood. Carbon monoxide is the gas most suitable by measuring the D_L.

The potential interactive effects of various air pollutants may pose a greater threat to human physiological performance than that found with each single pollutant. Pollutants may interact in three ways: (a) additively, (b) synergistically or (c) antagonistically (81). An additive interaction implies that the total physiological effect is simply the sum of the individual pollutant effects which is exemplified by ozone and nitrogen dioxide (57). In contrast, ozone and peroxyacetyl nitrate seem to display a synergistic effect (27) where the combined effect of the pollutants is greater than the sum of the individual pollutant effects. An antagonistic interaction, which has not been observed to date, results when the combined pollutant effects are less than the sum of the individual effects.

More recently, research interest has focused on human "adaptation" to the various pollutants, most noticeably ozone. Repeated daily exposure to ozone has been associated with an improved exercise performance by the third or fourth exposure day (46,59). However, several authors (20,46) caution that the acquired insensitivity to ozone or "adaptation" may not be protective, but rather repeated exposure to low

levels of this pollutant may be undesirable because of the potential for developing changes or injury to the lung. This same caution should be considered when studying "adaptation" to the other pollutants.

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INSERT FIGURE 2 ABOUT HERE

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The rate and severity of air pollution episodes is known to be influenced by environmental and meteorological factors not to mention the time of day. Figure 2 displays the daily and seasonal fluctuations for ozone and carbon monoxide. As shown in this figure, primary pollutants such as carbon monoxide and also the nitrogen oxides manifest daily peaks in clear association with peak traffic conditions and display their highest levels in mid-winter (81). Secondary pollutants such as ozone show a distinctive pattern related to the sunlight hours with peak daily values in the afternoon, and peak seasonal values in the summer or early autumn (81). In addition to sunlight, other meteorological factors known to influence the severity of air pollution episodes are the wind speed and the vertical temperature gradient.

The combination of certain pollutants with the environmental extremes of heat, cold or altitude may result in additive and/or synergistic effects. In addition, extremes in the percent relative humidity are known to be associated with adverse health effects. For instance, the adverse effects of sulfur dioxide become more pronounced at high humidity where ozone levels are enhanced by low humidity (12,81). Some authors (12) suggest an optimal range of 40 to 60% relative humidity to help minimize the performance degradation of these pollutants.

When the relative effects of environmental heat and adverse air quality are compared, heat would appear to be the more important stressor in terms of human performance. Several authors (28,49,95,96) report that heat stress was more effective in reducing human exercise performance than carbon monoxide and/or peroxyacetyl

nitrate. In contrast, the combination of heat stress and ozone has been shown to have an additive effect in reducing exercise performance (41,47).

Little direct experimental evidence exists concerning the combined effects of environmental cold and air pollution. However, breathing cold air during exercise has been shown to enhance bronchoconstriction (111). Whether the degree of bronchoconstriction would be further enhanced by certain air pollutants in combination with cold air exposure is worthy of investigation.

Carbon monoxide exposure is known to impair maximal exercise performance at sea level in terms of a reduced maximal aerobic power. At elevations greater than about 1500 meters, maximal aerobic power is known to decrease linearly (87). The hypoxic hypoxia which occurs during exercise at altitude is similar to that induced by carbon monoxide. One might expect the effects of carbon monoxide to be enhanced at altitude due to the reduction in mean capillary oxygen pressure (51).

THE PRIMARY POLLUTANTS

Carbon Monoxide

Carbon monoxide (CO) is reported to be the most commonly occurring of all the air pollutants in urban environments with the total emissions from this pollutant being greater than all other pollutants combined (44). Carbon monoxide is thought to impair cardiorespiratory function, particularly during physical exercise, by binding with hemoglobin in the blood (COHb) to impede oxygen transport. In fact, CO has a 200 times greater affinity for hemoglobin than that of oxygen, and is known to shift the oxygen dissociation curve to the left resulting in more difficult tissue oxygen extraction. In general, CO is associated primarily with motor vehicle emissions and the outdoor environment; however, CO toxicity has been reported for young hockey players skating in an indoor hockey rink and attributed to a gasoline-powered resurfacing machine (7).

Submaximal exercise performance. Little impairment of cardiorespiratory function and no major physical performance decrements have been reported in healthy individuals at COHb levels of less than 20% throughout a wide range of submaximal exercise intensities (30-75% $\dot{V}O_2$max) of both short and prolonged duration (31,49,90,112). Submaximal heart rate (HR) was found to be significantly increased with CO administration at these same exercise intensities (31,49,90,112), and added respiratory distress in terms of increased pulmonary ventilation ($\dot{V}_E$) was reported (31,112) at the higher submaximal intensities (70-75% $\dot{V}O_2$max). It should be remembered that the COHb levels reported in these studies (range, 10.7-20.1% COHb) are well above those normally associated with poor air quality (81).

In contrast to healthy individuals, cardiovascularly-impaired individuals are at significant risk during submaximal exercise even at low COHb levels (~2.5-3.0% COHb). In an investigation of 10 male patients with documented coronary artery disease, exposure for 90 min to heavy freeway traffic increased the average COHb level to 5.08% causing a decreased exercise time to angina onset with significant reductions in systolic blood pressure and HR at angina (10). In this same study, ischemic ST-segmental depressions were observed in three of these 10 men while breathing freeway air in contrast to no such abnormalities while breathing compressed-purified air during freeway traffic. In two investigations each studying 10 male patients with documented angina, exercise time for onset of angina was evaluated while breathing either 50 ppm CO (COHb=2.7%) for two hr (11), or 50 ppm CO (COHb=2.9%) and 100 ppm CO (COHb=4.5%) for four hr (4). During both studies at either CO concentration, average exercise angina onset times were reduced when compared to values while breathing compressed-purified air. In addition, the duration of angina was significantly prolonged after breathing 100 ppm CO, but not after breathing 50 ppm CO (4). In general, deeper and more prolonged ischemic ST-segmental depressions were noted in these patients after breathing CO (4).

Maximal exercise performance. In contrast to human performance during submaximal exercise, maximal exercise performance for healthy individuals in terms of maximal exercise time and/or $\dot{V}O_2max$ appears to be inversely related to the CO concentration (31,61,90,112). The critical level at which COHb significantly influences $\dot{V}O_2max$ has been reported as 4.3% (61). However, even lower COHb levels have been associated with significant decrements in maximal exercise time (28,95,96).

After maximal treadmill exercise in five young men at an average COHb level of 15.4%, Pirnay et al. (90) observed a 15.1% reduction in $\dot{V}O_2max$. These authors also noted a small ($\bar{X}$=2.4 $b \cdot min^{-1}$) but significant increase in HR_{max} and a relative hyperventilation with CO exposure. After maximal upright cycle ergometer exercise involving eight young male volunteers at an average COHb level of 20.5%, Vogel and Gleser (112) report a 22.6% reduction in $\dot{V}O_2max$ which was cited as proportional to the arterial desaturation. While maximal cardiac output ($\dot{Q}_{max}$), stroke volume (SV), HR_{max} and peak lactate concentrations were not different, peak $\dot{V}_E$ was lower during maximal exercise with CO (112). These same authors suggest that the leftward shift in the oxyhemoglobin dissociation curve with CO exposure and the associated decrease in oxygen carrying capacity can account for the entire decrement in $\dot{V}O_2max$. Ekblom and Huot (31) evaluated maximal cycle and treadmill exercise responses in ten well-trained subjects at COHb levels ranging from 4.8 to 21.2%. During either cycle (mean COHb=7.5 and 20.7%) or treadmill (mean COHb=7.1 and 19.3%) maximal exercise, average maximal exercise time and $\dot{V}O_2max$ were significantly reduced at all of these CO concentrations. For both types of maximal exercise, peak $\dot{V}_E$ and peak blood lactate concentrations remained unchanged while HR_{max} generally displayed a slightly lower value after CO exposure. During additional maximal treadmill exercise experiments over a wider range of COHb levels, the $\dot{V}O_2max$ (r=0.85) and maximal exercise time (r=0.79) predictively decreased with increasing COHb level (31). These

same authors conclude from an extrapolation of their findings that exercise time would be reduced to zero at 46% COHb.

Reports by Drinkwater et al. (28) and Raven et al. (96) appear to eminate from a common database involving 20 young men (10 smokers and 10 non-smokers) who exercised maximally by performing a modified Balke treadmill test. The $\dot{V}O_2$max was unchanged for these subjects with COHb levels ranging from 2.5-4.5%. The higher COHb levels were associated with the smokers. In one of these studies (28), the maximal exercise time was reduced for non-smokers during CO exposure. In a study of 16 older men (nine non-smokers and seven smokers) who performed maximal treadmill exercise, Raven et al. (95) report no significant reductions in $\dot{V}O_2$max with CO exposure (non-smokers COHb=2.3%, smokers COHb=4.5%). However, the older male smokers had a $\dot{V}O_2$max that was 27% less than the non-smokers of comparable age. In a study by Aronow and Cassidy (9), ischemic ST-segmental depressions of greater than 1.0 mm were noted in 10% of clinically normal individuals during maximal treadmill exercise following inhalation of 100 ppm CO (COHb, 3.95%). In this same study, maximal exercise time was significantly reduced with CO.

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INSERT FIGURE 3 ABOUT HERE

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In four male volunteers who exercised maximally on a treadmill, Horvath and colleagues (61) noted a 4.9 and 7.0% reduction in maximal exercise time when the levels of COHb were 3.3 and 4.3%, respectively. However, these same authors report that $\dot{V}O_2$max is not significantly decreased until COHb levels exceed 4.3%. Figure 3 illustrates the relationship between the percent increase in COHb and the associated percent decrement in $\dot{V}O_2$max (58). When COHb levels range from about 4 to 33%, there is a linear decline in $\dot{V}O_2$max expressed by the following formula: percent decrease in $\dot{V}O_2$max=0.91 (% COHb) + 2.2 (58). No studies have been reported to

our knowledge on human adaptation to CO during either submaximal or maximal exercise.

Sulfur Oxides

Sulfur oxides (SO_x) result from fossil fuel combustion and include primarily sulfur dioxide (SO_2), sulfuric acid and sulfate. It is estimated that about 98% of the atmospheric sulfur from the burning of fossil fuels is initially in the form of SO_2 which may convert to sulfuric acid and sulfate (81). Sulfur dioxide is a highly soluable gas which exerts its main influence as an upper respiratory tract irritant and can cause a reflex bronchoconstriction and increased pulmonary resistive flow. As indicated earlier, the shift from nose to mouth breathing known to occur during physical exercise will result in less efficient absorption of SO_2 and consequently greater pulmonary flow resistance as illustrated in Figure 4. While submaximal exercise performance has been evaluated with this pollutant, no studies have been reported concerning maximal exercise performance.

INSERT FIGURE 4 ABOUT HERE

Submaximal exercise performance. Eight healthy young males performed intermittent cycling exercise for two hrs (15 min exercise, 15 min rest) at an exercise intensity sufficient to double their pulmonary ventilation while breathing 0.37 ppm SO_2 (57). These authors observed no significant effect on ventilatory function as exemplified by the maximum mid-expiratory flow rate (MMFR) at this SO_2 concentration. In a study of four sensitive subjects (respiratory hyperractivity to inhaled irritants) using the same experimental protocol and SO_2 concentration as Hazucha and Bates (57), Bell et al. (19) confirmed that 0.37 ppm SO_2 had no effect on FVC, $FEV_{1.0}$ and delta N_2. At 0.40 ppm SO_2, Bedi et al. (17) had nine adult men perform intermittent treadmill exercise (15 min walk, 15 min rest) for two hrs which elevated $\dot{V}_E$ during exercise to

30 $\ell \cdot min^{-1}$. This SO_2 concentration was insufficient to produce significant pulmonary function differences (i.e., FVC, $FEV_{1.0}$, IC, FRC, RV, TLC, $FEF_{25-75\%}$, $FEF_{50\%}$, $FEF_{75\%}$, MVV, R_{aw} and CV). While exposed to 0.75 ppm SO_2 for four hrs, eleven healthy men performed two 15-min bouts of treadmill walking (1.78 $m \cdot s^{-1}$, 10% grade). Evaluation from a battery of 19 measurements of pulmonary function indicated that the airway resistance, lung volume and air flow responses to 0.75 ppm SO_2 were not significantly altered (109). At a concentration of 1.0 ppm SO_2, Folinsbee et al. (38) had 22 healthy young men exercise intermittently on a treadmill (walking, 1.56 $m \cdot s^{-1}$) for two hrs (30 min exercise, 10 min rest) with the exercise adequate to elevate the $\dot{V}_E$ to 38 $\ell \cdot min^{-1}$. However, this SO_2 concentration was reported to be below the threshold for significant pulmonary effects as shown from measurements of FVC, $FEV_{1.0}$, $FEF_{25-75\%}$, and specific airway conductance (38). In contrast, Snell and Luchsinger (108) report a small but significant decrease in the maximum expiratory flow from one half total capacity ($MEF_{50\%VC}$) following 15 min inhalation of 1.0 ppm SO_2 by mouth in nine healthy adult volunteers. However, Kreisman et al. (71) evaluated eight trained subjects during light cycling exercise (~50 W) at 1.0 ppm SO_2 and reported no significant changes in maximal expiratory flow rate as an index of respiratory function.

At a concentration of 3.0 ppm SO_2, Kreisman et al. (71) demonstrate a significant decrease in the maximal respiratory flow rate in nine subjects during light cycling exercise (~50 W). In additional experiments utilizing the same experimental protocol and test subjects mentioned, Snell and Luchsinger (108) show more pronounced decreases in $MEF_{50\%VC}$ at 5.0 ppm SO_2. At 5.0 ppm SO_2, Wolff et al. (118) evaluated mucociliary transport during cycling exercise for 30 min at an intensity estimated to require 70-75% of HR_{max}. This author reports that the rate of mucociliary transport was higher during exercise at 5.0 ppm SO_2 suggesting possible

impairment with this defense mechanism for removal of airborne particles from the respiratory tract. In conclusion, it would appear that the threshold level of SO_2 which affects human physiological performance in healthy individuals during submaximal exercise is between 1.0 and 3.0 ppm SO_2.

Asthmatic individuals and possibly others with pulmonary hyperractivity appear to have a lower threshold and greater bronchomotor responsiveness during SO_2 exposure at rest (65,79,104,105). In seven asthmatic adult volunteers performing moderate cycle exercise at 67 W (400 kpm•min^{-1}) for 10 min, Sheppard et al. (104) report a significant increase in specific R_{aw} at 0.50 ppm of SO_2. In their two most responsive asthmatic subjects, inhalation of 0.10 ppm SO_2 at this same exercise intensity also significantly increased the specific R_{aw}. During exposure to 0.50 ppm SO_2 while performing cycle exercise for 5 min at 92 W (550 kpm•min^{-1}), Kirkpatrick et al. (65) evaluated six adult asthmatic subjects during either oral, nasal or oronasal breathing. For these asthmatic individuals, nasal breathing provided slightly more protection against increases in specific R_{aw} during exercise, but both oral and oronasal breathing of 0.50 ppm SO_2 resulted in significant bronchoconstriction in these people. In 23 asthmatic volunteers who performed 5 min of heavy cycling exercise at a mean power output of 122 W (730 kpm•min^{-1}), Linn et al. (79) evaluated SO_2 concentrations of 0.0, 0.2, 0.4 and 0.6 ppm. Pulmonary measurements included thoracic gas volume (V_{tg}), specific R_{aw}, FVC, $FEV_{1.0}$, $FEV_{2.0}$, $FEV_{3.0}$, peak expiratory flow rate (PEFR) and flow rates with 75, 50 and 25% FVC remaining. These authors report highly significant changes in most of these pulmonary measures at 0.60 ppm SO_2, few changes at 0.40 ppm and no significant changes at 0.20 ppm. Thus, the threshold concentration of SO_2 for asthmatics during submaximal exercise would appear to be between 0.20 and 0.50 ppm of SO_2.

Adaptation. Several studies suggest that healthy and asthmatic individuals may adapt to SO_2, but unfortunately none of this research investigated adaptation to SO_2 during physical exercise. In an investigation of industrial workers who were exposed on a regular basis to concentrations of 10 ppm SO_2, Amdur et al. (5) report that these individuals were not responsive to levels of 5 ppm SO_2 as shown in non-exposed individuals. Anderson et al. (3) conducted experiments involving 15 young men exposed for six hrs to levels of 1, 5 or 25 ppm SO_2 where the SO_2 level was slowly increased during the initial 1 to 1 1/2 hrs of exposure to reach the target concentration. These same authors state that the test subjects tolerated all levels including 25 ppm "very well", possibly due to the very slow rise to the target level, but the experimenters who had to occasionally enter the chamber were quite disturbed by the seemingly abrupt changes in SO_2 level and found the 25 ppm level to be an "almost intolerable discomfort". In eight asthmatic subjects performing 3 min of voluntary eucapnic hyperpnea at 0.50 ppm SO_2 repeated three times at 30-min intervals, Sheppard et al. (103) show significantly greater tolerance in terms of specific R_{aw} with each repeated exposure.

Nitrogen Oxides

The nitrogen oxides (NO_x) develop from high temperature combustive processes involving nitrogen and oxygen with elevated levels being prevalent during heavy motor vehicle use, with aircraft at airports; and, the smoke associated with cigarettes or fire fighting. Motor vehicles have been suggested to account for about 40% of the NO_x emissions (81). The nitrogen oxides include nitrous oxide, nitric oxide, nitrogen dioxide, dinitrogen trioxide, dinitrogen pentoxide and nitrate ions. Of these, nitrogen dioxide (NO_2) is known to be potentially harmful to health and is the only NO_x studied to any extent in man. Acute exposure to high concentrations of NO_2 (estimated range, 200-4000 ppm) in farmers filling silos (silo-filler's disease) was

associated with early severe pulmonary edema, subsequent bronchiolitis fibrosa obliterans, and ultimately death in two of the four exposed individuals (80). Some suggest that those individuals with chronic bronchitis, chronic obstructive pulmonary disease and possibly other respiratory disorders may be highly susceptible tc the adverse effects of NO_2 exposure.

Submaximal exercise performance. With a shift from nasal to oral breathing which occurs during physical exercise, less NO_2 is absorbed while more of this pollutant reaches the small airways and alveoli resulting in increased airway resistance. Only a few studies involving intermittent light to moderate physical exercise have evaluated the singular effects of NO_2. Maximal exercise responses to this pollutant have not been reported to date.

Sixteen healthy male volunteers performed intermittent light cycling exercise for two hrs (15 min exercise, 5 min rest) while exposed to 1.0 ppm NO_2 (56). The exercise intensity was sufficient to double the resting ventilation. Most of the pulmonary function tests and associated measurements which were described earlier in the Introduction to this chapter were evaluated in this study. These authors report no statistically significant pulmonary function changes associated with NO_2 exposure except for a marginal loss in FVC after NO_2 exposure for two consecutive days. However, these same authors suggest that the long term effects of this pollutant need to be evaluated as well as its effects on individuals with pulmonary hyperractivity.

Posin et al. (92) evaluated the blood biochemical changes of ten healthy young men who were exposed to concentrations of either 1 or 2 ppm NO_2 while performing light exercise for 2.5 hrs employing a previously described experimental protocol (56). At both NO_2 concentrations, decreases were reported for hemoglobin, hematocrit and erythrocyte membrane enzyme actylcholinesterace. Levels of peroxidized red blood cell lipids were increased only at 2 ppm NO_2 while glucose-6-phosphate dehydrogenase was

elevated only after two exposures to the higher NO_2 concentration. These authors conclude that minimal but significant blood biochemical changes were associated with NO_2 inhalation; however, the experimental procedures appeared to contribute to some of these changes.

Fifteen healthy young men were exposed for two hrs to 0.62 ppm NO_2 while exercising at 45% $\dot{V}O_2$max for various time periods (40). Of the two hr exposure period, exercise involved 15, 30 or 60 min. Pulmonary function measurements included: TV, FVC, $FEV_{1.0}$, $FEF_{25-75\%}$, $FEF_{50\%}$, $FEF_{75\%}$, IC, ERV, FRC, MVV and R_{aw}. There appear to be no profound alterations in these pulmonary functions and other cardiorespiratory responses during intermittent exercise at concentrations of 0.62 ppm NO_2 (40). While inhaling 0.50 ppm NO_2 for four hrs, 10 healthy men performed two 15-min bouts of treadmill walking (1.78 $m \cdot s^{-1}$, 10% grade) which resulted in no significant effects on a battery of 19 measurements of pulmonary function (109).

From these limited number of studies, NO_2 exposure does not appear to adversely affect human physiological performance during submaximal exercise in healthy individuals. No studies have been reported to date on human adaptation to NO_2 during physical exercise.

Primary Particulates

Primary particulate matter mainly includes dust, soot and smoke (81,88). Soot emanates primarily from the incomplete combustion of fossil fuels and environmental erosion, while the major sources of dust and smoke include dust storms, forest fires, wind storms and volcanos. The receptor site reached by particulate matter is determined by the particle size with the frequency of breathing, tidal volume and other factors, such as nasal versus oral breathing influencing total particle disposition (22). Thus, elevated levels of particulate matter may increase the effective dose of this type of pollutant for individuals performing physical exercise. However, the physiological

performance effects of particulates have not been directly evaluated using exercise in man.

In man, inhalation of fine charcoal dust (117), inert dust particles (30) or cigarette smoke particles (86) results in a decreased airway conductance and an increased airway resistance. After inhalation of fine charcoal dust in nine healthy men, Widdicombe et al. (117) report an average decrease of 41% for airway conductance (increased resistance) and an associated bronchoconstriction. After breathing inert dust particles in five healthy middle-age men, Dubois and Dautrebande (30) observed a significant increase in airway resistance and pulmonary resistance with often a slight decrease in lung compliance. In 36 healthy subjects (21 smokers and 15 non-smokers) and 22 patients with diagnosed cardiopulmonary disease (all smokers) after inhaling 15 puffs of cigarette smoke in a five-min period, Nadel and Comroe (86) show a significant decrease in the airway conductance/thoracic gas volume ratio. These same authors suggest that these changes are not dependent on nicotine or the nitrogen oxides in cigarette smoke, but are probably related to the submicronic particle matter (86).

In general, particles greater in size than 10 microns are not suitable for respiration while particles less than 5 microns can cause adverse health effects such as inflammation, congestion and/or ulceration (58,81). Particles between 3 and 5 microns usually settle in the upper respiratory tract while particles between 0.5 and 3 microns generally reach the alveoli (81). Larger particles are generally discharged from the respiratory tract faster than smaller particles (72). Phagocytosis and muscus transport are the usual processes employed for lung clearance after particle inhalation (64).

The question of adaptation to atmospheric particles in man is limited to the inferential observations from one study. In three healthy human subjects who repeatedly inhaled aluminum dust (mean size=0.68 microns) three times between short

intervals of normal air breathing. Dautrebande et al. (23) concludes that the pneumoconstriction became greater and respiration more frequent with each dose of dust. Thus, at least for dust, adaptation in man appears questionable.

THE SECONDARY POLLUTANTS

Ozone

Ozone (O_3) is produced in oxygen containing atmospheres primarily from the interaction of hydrocarbons and nitrogen dioxide in the presence of solar ultraviolet radiation. As illustrated earlier in Figure 2, the O_3 level is related to the sunlight hours and usually reaches peak concentrations near midday. Whereas the current U.S. air quality standard for O_3 is 0.12 ppm (one hour averaging time), Kleinfeld and Giel (66) report three case studies of ozone poisoning in male welders exposed to 9.2 ppm O_3 while Kelly and Gill (63) describe O_3 poisoning in a male industrial crane operator with all cases leading to severe and prolonged illness. Kelly and Gill (63) further state that inhalation of 50 ppm O_3 for 30 min could be fatal.

Submaximal exercise performance. Ozone is a potent airway irritant capable of causing a reflex bronchoconstriction in the upper airways at sufficient concentrations. In 12 healthy volunteer subjects exposed to 0.20 ppm O_3 for two hrs with intermittent light cycling exercise (33-50 W) capable of doubling the resting pulmonary ventilation, Linn et al. (75) report no significant adverse effects on arterial blood oxygenation or lung mechanics. After two hrs of intermittent light cycling exercise (15 min exercise, 15 min rest) adequate to double the pulmonary ventilation of eight healthy young men breathing 0.37 ppm O_3, Hazucha and Bates (57) report a "just significant decrease" in maximal mid-expiratory flow rate (MMFR) at the end of this two hr exposure. In four normal and four sensitive volunteer subjects, Bell et al. (19) attempted to reproduce the observations of Hazucha and Bates (57) in Los Angeles residents. While exposed to the same O_3 level (0.37 ppm) and experimental methodology as the earlier study

(57), these authors (19) did not observe significant changes in mean pulmonary functions (FVC, $FEV_{1.0}$, TLC, RV, ΔN_2, closing capacity, and flow rates with 50% and 25% FVC remaining) at this O_3 concentration. After two hrs of intermittent treadmill walking and rest (15 min walk, 15 min rest) which was sufficient to produce a $\dot{V}_E$ of 30 $\ell \cdot min^{-1}$ in nine young adult men breathing 0.40 ppm O_3, Bedi et al. (17) report significant decreases in maximum expiratory flow ($FEV_{1.0}$, $FEF_{25-75\%}$ and $FEF_{50\%}$), FVC and IC. In six healthy young adults who inhaled 0.45 ppm O_3 for two hrs while performing intermittent light cycle exercise (33-75 W) yielding a $\dot{V}_E$ of 27 $\ell \cdot min^{-1}$, Bedi et al. (16) display significant decrements in FVC, $FEV_{1.0}$, $FEV_{3.0}$, $FEF_{25-75\%}$, and TLC; however, $\dot{V}_E$, $\dot{V}O_2$, and $\dot{V}CO_2$ were not significantly altered at this O_3 level.

During moderate treadmill exercise (1.56 $m \cdot s^{-1}$, up an incline) for two hrs (30 min exercise, 10 min rest) producing a $\dot{V}_E$ of 38 $\ell \cdot min^{-1}$ in 22 young adult men while breathing 0.30 ppm O_3, Folinsbee et al. (38) report significant reductions in forced expiratory measurements (FVC, $FEV_{1.0}$ and $FEF_{25-75\%}$). While inhaling 0.40 ppm O_3 for four hrs, 12 healthy men performed two 15-min bouts of treadmill walking (1.78 $m \cdot s^{-1}$, 10% grade) which resulted in significant decreases in specific R_{aw}, FVC and $FEF_{50\%}$ (109). In a comparison of six female and six male subjects who performed three intensities of cycling exercise (~30-60% $\dot{V}O_2max$) for one hr each at 0.0, 0.20, 0.30 or 0.40 ppm O_3, Lauritzen and Adams (73) show greater decrements in FVC, $FEV_{1.0}$ and respiratory rate for the females at the same total O_3 effective dose as the males. These same females displayed an increased $\dot{V}_E$ with O_3 exposure, but no effect on $\dot{V}O_2$ and HR. A sample of 135 healthy male volunteers divided into six groups was exposed to intermittent moderately heavy treadmill exercise (15 min rest, 15 min exercise sufficient to increase $\dot{V}_E$ to 65 $\ell \cdot min^{-1}$) either at 0.0, 0.12, 0.18, 0.24, 0.30 or 0.40 ppm O_3 (83). While coughing occurred at all levels of O_3 exposure, McDonnell et al. (83) report small changes in FVC, $FEV_{1.0}$ and $FEF_{25-75\%}$

at 0.12 and 0.18 ppm O_3 with larger changes at O_3 concentration equal to or greater than 0.24 ppm. During exercise, these same authors note alterations in TV, specific R_{aw} and respiratory rate accompanied with increased subjective distress at O_3 levels greater than or equal to 0.24 ppm (83). While breathing 0.15 or 0.30 ppm O_3 for one hr, DeLucia and Adams (25) evaluated the performance of six healthy males during cycle exercise at 25, 45 or 65% $\dot{V}O_2$max, and reported no changes in $\dot{V}_E$, $\dot{V}O_2$ or blood biochemistry at any exercise intensity. However, all subjects showed some signs of toxicity at 45 and 65% $\dot{V}O_2$max with significant decrements in VC, $FEV_{1.0}$ and MMFR observed at 65% $\dot{V}O_2$max while inhaling 0.30 ppm O_3. During moderately heavy cycling exercise (45-75% $\dot{V}O_2$max) which immediately followed two hrs of exposure to 0.37, 0.50 or 0.75 ppm O_3, Folinsbee et al. (43) show no significant alterations in submaximal $\dot{V}O_2$, HR or $\dot{V}_E$ at any of these O_3 levels. However, other measurements of pulmonary function such as TV and respiratory rate appeared to be somewhat disturbed by O_3 exposure. In an evaluation of the threshold for O_3 toxicity during cycling exercise, Adams et al. (1) had eight trained male volunteers complete 18 different protocols involving three O_3 levels (0.20, 0.30 and 0.40 ppm), two exercise intensities ($\dot{V}_E$=33 and 66 $\ell \cdot min^{-1}$), and different exercise durations between 30 and 80 min. These same authors report the threshold for O_3 toxicity to involve moderately heavy exercise (~65% $\dot{V}O_2$max) at O_3 levels between 0.20 and 0.30 ppm.

During heavy cycling exercise (75% $\dot{V}O_2$max) for one hr involving seven trained athletes exposed to 0.21 ppm O_3, Folinsbee et al. (37) show significant decreases in FVC, $FEV_{1.0}$, $FEF_{25-75\%}$ and MVV with the magnitude of these alterations similar to those seen during moderate intermittent exercise at 0.24 ppm O_3 for two hrs. Symptoms of distress were also quite severe (37). While breathing 0.0, 0.20 or 0.35 ppm O_3 during one hr of cycle exercise which simulated training or competition (30 min at ~85% $\dot{V}O_2$max), Adams and Schelegle (2) evaluated the performance of 10

well-trained runners and reported no significant changes in HR, $\dot{V}O_2$, $\dot{V}_E$ and alveolar ventilation with O_3 exposure, but showed significant decrements in FVC and $FEV_{1.0}$ with enhanced subjective symptoms during O_3 exposure. Three of these 10 subjects were not able to complete the training and competitive simulations at 0.35 ppm O_3 because of respiratory discomfort (2). Employing a similar experimental design to that described above (2), Schelegle and Adams (100) exposed 10 competitive endurance athletes while breathing either filtered air, 0.12, 0.18 or 0.24 ppm O_3 to a one hr competitive simulation cycling protocol (30 min at ~86% $\dot{V}O_2max$). While no difference in HR, $\dot{V}O_2$, $\dot{V}_E$, respiratory rate or TV with O_3 were found, these authors show a general increase in the inability to complete these simulations with increasing O_3 concentration (significant at 0.24 ppm O_3) which appeared to be primarily associated with enhanced subjective symptoms of distress. During two hrs of heavy intermittent treadmill exercise (1.30 $m \cdot s^{-1}$, 15% grade; 15 min rest, 15 min exercise) involving 23 boys (8-11 yr) exposed to 0.12 ppm O_3, McDonnell et al. (82) report small decrements in $FEV_{1.0}$ without induction of cough or any changes in exercise $\dot{V}_E$ or HR.

In summary, submaximal exercise performance at light to moderate exercise intensities during O_3 exposure does not appear to be limited in terms of the cardiorespiratory system; however, decrements in pulmonary functions and enhanced subject discomfort become apparent. At heavy intensities of submaximal exercise, O_3 exposure can limit performance primarily from severe respiration discomfort and associated changes in pulmonary functions without altering cardiorespiratory responses.

Maximal exercise performance. In contrast to submaximal exercise performance, the literature concerning maximal exercise performance and O_3 exposure in man is quite limited. After two hrs of intermittent light cycling exercise involving 13 adult men breathing either filtered air (FA) or 0.75 ppm O_3, Folinsbee et al. (42) measured

cycling $\dot{V}O_2max$ and reported a 10% reduction with 0.75 ppm O_3 compared to FA. Reductions were also observed for maximal exercise intensity (10%), maximal $\dot{V}_E$ (16%) and HR_{max} (6%) during O_3 exposure. In a study of nine healthy men following 30 min of breathing either 0.00, 0.15 or 0.30 ppm O_3, Savin and Adams (99) show no change in anaerobic threshold, exercise capacity or cycling $\dot{V}O_2max$ associated with O_3 concentration. After two hrs of resting exposure to 0.00, 0.25, 0.50 or 0.75 ppm O_3 in eight men and five women, Horvath et al. (60) report no significant changes in treadmill $\dot{V}O_2max$, HR_{max} or maximal performance time associated with O_3 exposure. Thus, maximal exercise performance may be lowered at relatively high O_3 levels, but further research is necessary in order to support this claim.

Adaptation. Human adaptation to O_3 exposure was initially suggested from experimental observations involving residents of Southern California who were chronically exposed to elevated levels of O_3 and were less sensitive to this pollutant than Canadian residents who are far less often exposed to O_3 (19,52). After exposure for four consecutive days (two hrs/day) to 0.50 ppm O_3 in six male volunteers with respiratory hyperractivity, Hackney et al. (54) reports pulmonary function decrements during the first three days of exposure which were mostly reversed by the fourth day which suggests adaptation. In a study of 14 healthy subjects (10 men and 4 women) exposed for five consecutive days (three hrs/day) to 0.40 ppm O_3, Farrell et al. (33) suggests that the maximal response to O_3 in terms of impaired pulmonary functions occurred for most subjects on the second exposure day with adaptation thereafter. A series of experiments (39,48,59) concerning adaptation to O_3 which typically employed a two hr exposure with intermittent exercise at various O_3 concentrations (0.20, 0.35, 0.42 or 0.50 ppm) and involved 75 volunteer subjects (62 men and 13 women) has been summarized by Folinsbee et al. (35). It can generally be concluded from these experiments that adaptation to consecutive daily exposures of O_3 varies from two to

five days, lasts for less than two weeks (range, 7-20 days) and does not differ between genders (35,39,48,59). Figure 5 illustrates the number of consecutive days required to produce adaptation to 0.42 ppm O_3 for 24 of these subjects (35). After exposure to 0.20 or 0.40 ppm O_3 for two hrs on three to five consecutive days in two groups of healthy adult volunteers (n=7 each group), Dimeo et al. (26) shows peak changes in bronchial reactivity to occur after the first or second exposure with adaptation after the third, fourth or fifth exposure. In a group of 11 generally healthy volunteers exposed initially to 0.47 ppm O_3 for four consecutive days (two hrs per day with intermittent exercise) and then after a four-day interval without exposure followed by seven-day intervals for four weeks, Linn et al. (78) report peak changes in $FEV_{1.0}$ and subjective symptoms on the second consecutive exposure day with adaptation generally appearing on the fourth exposure day. These authors also state that adaptation is partly lost after a four-day interval without O_3 exposure and seems to be completely lost after a seven-day interval. In a recent study of eight trained males exposed to 0.35 ppm O_3 for four consecutive days (one hr per day), Foxcroft and Adams (46) report significant decrements in $\dot{V}O_2max$, maximal exercise performance time and pulmonary functions on the first exposure day with significant improvement in $\dot{V}O_2max$ and maximal exercise time but not impaired pulmonary functions after the fourth consecutive exposure day. While adaptation is seen to occur after two to five days of consecutive exposure to O_3, it should be remembered that this adaptation may be eventually harmful to man because of the associated suppression of normal defense mechanisms (81).

INSERT FIGURE 5 ABOUT HERE

Peroxyacetyl Nitrate

Peroxyacetyl nitrate (PAN) regarded as a secondary pollutant was first detected in the exhaust of motor vehicles in the early 1950s (81). This pollutant is known to cause eye irritation and ocular function disturbances while producing some pulmonary function alterations in man. Relatively few studies have investigated the effects of PAN during submaximal and/or maximal exercise while no research has been reported concerning adaptation to this pollutant.

Submaximal exercise performance. During submaximal treadmill exercise (35% $\dot{V}O_2$max) of 210 min duration while breathing 0.24 ppm PAN, no remarkable changes in cardiorespiratory, metabolic or thermoregulatory responses were observed in either younger (22-26 yr, n=10) or older (45-55 yr, n=9) healthy male volunteers (49,97). These responses included $\dot{V}O_2$, $\dot{V}_E$, $\dot{V}_E/\dot{V}O_2$, HR, cardiac index, rectal temperature (T_{re}) and mean skin temperature (T_{sk}). There were no differences in these responses related to age (49). In these same experiments, FVC was reduced 4-7% in the younger subjects with PAN, but the significance is questionable (97). Other pulmonary function measures ($FEV_{1.0}$, $FEV_{2.0}$, $FEV_{3.0}$, $FEV_{1.0}$/FVC%, MMFR, IC and ERV) showed no significant differences due to this pollutant (97). Subjective complaints of eye irritation, blurred vision and eye fatigue were inhanced in the presence of PAN (49). The concentration of PAN (0.24 ppm) in these few experiments may be at or slightly below the threshold level needed for demonstrable physiological effects which might suggest additional studies during submaximal exercise at slightly higher concentrations. Nevertheless, some minor changes in pulmonary function and subjective discomfort have been observed to date during prolonged exposure to PAN with little change in cardiorespiratory, metabolic or thermoregulatory responses during light submaximal exercise.

Maximal exercise performance. During maximal exercise involving a modified treadmill Balke test while breathing 0.27 ppm PAN, Raven et al. (96) report no significant decrement in $\dot{V}O_2$max for 20 healthy men (range, 21-30 yr) who were divided in two groups (10 non-smokers and 10 smokers). In another study from the above mentioned laboratory utilizing similar test methodology but evaluating 16 somewhat older men (range, 40-57 yr) divided into two groups (9 non-smokers and 7 smokers), Raven et al. (95) show no significant change in $\dot{V}O_2$max while breathing 0.27 ppm PAN. In addition, these same authors report no alterations in maximal $\dot{V}_E$, HR_{max}, maximal respiration rate, maximal time walked, post-exercise lactate and oxygen debt associated with breathing 0.27 ppm PAN. While the concentration of 0.27 ppm PAN is seemingly below the threshold to become physiologically meaningful for healthy individuals in a thermally comfortable environment, these authors caution that this PAN concentration might be a threshold level for other groups such as those with pulmonary impairments (95). Therefore, it would seem premature, particularly regarding maximal exercise performance, to conclude that PAN has no adverse effects on exercise performance until higher concentrations of this pollutant are evaluated, and at risk individuals are studied.

Aerosols

Of those investigations concerning the effects of aerosol pollutants in man, the majority have involved the study of sulfate aerosols, and sulfuric acid (H_2SO_4) or nitrate aerosols (109). The sulfate aerosols which are ammonia neutralization products of (H_2SO_4) are ammonium sulfate [$(NH_4)_2SO_4$] and ammonium bisulfate (NH_4HSO_4) while the nitrate aerosol most studied is ammonium nitrate (NH_4NO_3). Other reports have investigated SO_2 combined with sodium chloride (NaCl) aerosol; and, saturated and unsaturated aldehydes. Not all of these reports have included the effects of physical exercise in their evaluation of these aerosol pollutants.

Sulfate aerosols. In a study involving two hr exposures with light intermittent cycle exercise (25-50 W; 15 min exercise, 15 min rest) to either $(NH_4)_2SO_4$ or NH_4HSO_4 at a concentration of 100 $\mu g/m^3$, Avol et al. (13) evaluated both healthy (n=12) and asthmatic (n=12) adult men, and reported no significant adverse changes in pulmonary functions or recorded clinical symptoms. After four hr exposures including two, 15 min treadmill exercise sessions (1.78 $m \cdot s^{-1}$, 10% grade) involving healthy male volunteers in either 133 $\mu g/m^3$ $(NH_4)_2SO_4$ (n=13) or 116 $\mu g/m^3$ NH_4HSO_4 (n=15), Stacy et al. (109) also observed no significant changes in a battery of 19 measurements of pulmonary function. Thus, the sulfate aerosols at "worst case" ambient concentrations elicit minimal adverse effects relative to some of the other pollutants.

Sulfuric acid. After 5-15 min resting exposures of 15 normal human subjects to a concentration range of 350 to 5000 $\mu g/m^3$ H_2SO_4, Amdur et al. (6) observed shallower and more rapid breathing as a function of increasing concentration with the retention of inhaled H_2SO_4 averaging 77%. In a study of normal (n=17) and asthmatic (n=17) adults breathing H_2SO_4 aerosol in concentrations up to 1000 $\mu g/m^3$ for 10 min, Sackner et al. (98) report no changes in lung volumes, distribution of ventilation, ear oximetry, dynamic breathing mechanics, oscillation mechanics of the chest-lung wall, pulmonary capillary blood flow, D_L, $\dot{V}O_2$ and pulmonary tissue volume. While breathing 100 $\mu g/m^3$ H_2SO_4 in six normal and six asthmatic subjects utilizing the experimental methodology described in the previous paragraph, Avol et al. (13) showed no significant changes in pulmonary functions and subjective symptoms. At a concentration of 100 $\mu g/m^3$ H_2SO_4 in 11 healthy males also employing the same test methodology described in the previous paragraph, Stacy et al. (109) demonstrated no significant alterations in a battery of 19 tests for pulmonary function. In experiments involving 10 healthy non-smokers exposed for one hr to concentrations of 110, 330 or 980 $\mu g/m^3$ H_2SO_4 during rest, Leikauf et al. (74) observed marked alterations in

bronchial mucociliary clearance displaying a dose dependent pattern for these subjects. Thus, H_2SO_4 does not appear to be harmful to cardiorespiratory function for single brief exposures within the concentration range discussed; however, prolonged exposures, multiple exposures, larger aerosol particles and high relative humidity could cause this pollutant to have adverse effects on man.

Nitrate aerosols. In a study involving two hr exposures with light intermittent cycle exercise (25-50 W; 15 min exercise, 15 min rest) at a concentration of 200 $\mu g/m^3$ NH_4NO_3, Kleinman et al. (68) examined 20 normal and 19 asthmatic adult volunteers and reported no substantial changes in pulmonary functions or overall reported symptoms associated with this pollutant. At a concentration of 80 $\mu g/m^3$ NH_4NO_3 in 12 healthy male volunteers using the same methodology previously described, Stacy et al. (10) showed no adverse effects on a battery of 19 pulmonary function measurements with this pollutant. While somewhat limited, the experimental evidence does not support major alterations in respiratory responses associated with this pollutant aerosol.

Sulfur dioxide and sodium chloride droplet aerosol. In resting experiments of 60 min duration in nine adolescent asthmatic subjects exposed to 1 ppm SO_2 plus 100 $\mu g/m^3$ NaCl droplet aerosol, Koenig et al. (69) report significant decreases in maximal flow at 50 and 75% of expired vital capacity ($\dot{V}_{max50}$ and $\dot{V}_{max75}$) with no changes in FRC, FEV, and total respiratory resistance (R_T). After 30 min rest followed by 10 min of intermittent treadmill exercise (1.07 $m \cdot s^{-1}$, 12% grade) involving eight adolescent asthmatic volunteers exposed to 1 ppm SO_2 plus 1000 $\mu g/m^3$ NaCl, Koenig et al. (70) observed significant changes in $\dot{V}_{max50}$, $\dot{V}_{max75}$, $FEV_{1.0}$ and R_T with no change in FRC. However, these same authors could not certify that these exposure effects were due to the mixture (SO_2+NaCl) rather than SO_2 alone.

Saturated and unsaturated aldehydes. During 5-30 min exposures to formaldehyde (12 males, 13.8 ppm), acrolein (12 males each, 0.80 ppm and 1.22 ppm), crotonaldehyde (12 males, 4.1 ppm), acetaldehyde (14 males, 134 ppm), propionaldehyde (12 males, 134 ppm), butyraldehyde (15 males, 230 ppm) and isobutyraldehyde (15 males, 207 ppm), Sim and Pattle (106) observed that acrolein and crotonaldehyde were highly irritant while acetaldehyde, proprionaldehyde, butyraldehyde and isobutyraldehyde were essentially non-irritant. Formaldehyde was intermediate in terms of irritability compared to these two groups.

A summary of the effects of all of the air pollutants discussed thus far on submaximal or maximal exercise performance in normal individuals is presented in Table 3. This table is an updated version of a previously published table by the author (87).

INSERT TABLE 3 ABOUT HERE

INTERACTIONS BETWEEN POLLUTANTS

As discussed in the Introduction to the chapter, the various air pollutants may interact in three ways: (a) additively, (b) synergistically, or (c) antagonistically. The differentiation between additive and synergistic effects is frequently difficult and usually involves the specific pollutant concentration (8). No pollutant interactions have been reported that are antagonistic.

Additive Interactions

Ozone in combination with nitrogen dioxide has been studied at various concentrations (O_3=0.25-0.50 ppm, NO_2=0.30-0.50 ppm) during light to moderate intermittent exercise of two to four hr duration (36,53,55). In general, the effects attributed to O_3 alone were not increased with O_3 and NO_2 in combination. Exposure to NO_2 has been shown earlier in this chapter not to produce significant effects during submaximal exercise. Thus, this interaction is defined as additive.

In two of the above mentioned studies (53,55), CO at a concentration of 30 ppm was evaluated in combination with O_3 (0.25-0.50 ppm) and NO_2 (0.30 ppm) during light intermittent exercise of two to four hr duration in healthy and sensitive individuals. It has been demonstrated that CO does not produce significant effects during submaximal exercise. The addition of CO to the pollutant mixture (O_3+NO_2) failed to produce detectable effects and, therefore, this three-pollutant interaction is deemed additive.

Ozone in combination with total suspended particulates (TSP) has been evaluated at various concentrations (O_3=0.15-0.22 ppm, TSP=200-295 $\mu g/m^3$) during light to heavy intermittent or continuous exercise of one to two hr duration in healthy and/or asthmatic individuals (14,15,76). The combined exposure to O_3 and TSP produced generally the same response as O_3 separately at the same concentration. Thus, this interaction is defined as additive by inference.

In a series of experiments involving a total of 137 healthy male volunteers during moderate intermittent exercise of four hr duration, Stacy et al. (109) evaluated the effects of O_3, NO_2 and SO_2 <u>each</u> in combination with H_2SO_4, $(NH_4)_2SO_4$, NH_4HSO_4, or $NO_2H_2SO_4$. The concentrations of these pollutants were 0.40 ppm O_3, 0.75 ppm SO_2, 0.50 ppm NO_2, 100 $\mu g/m^3$ H_2SO_4, 133 $\mu g/m^3$ $(NH_4)_2SO_4$, 116 $\mu g/m^3$ NH_4HSO_4 and 80 $\mu g/m^3$ NH_4NO_3. None of the four aerosols separately, NO_2 or SO_2 separately, or combinations of NO_2 or SO_2 with any of the four aerosols caused significant effects. Therefore, these interactions would be termed additive. The response of O_3 with some of the aerosols, particularly O_3 and H_2SO_4, produced effects greater than those for O_3 separately; however, the statistical criteria for this apparent synergistic response was not quite significant.

The oxides of nitrogen and sulfur when combined have been cited by McCafferty (81) to demonstrate additive effects with SO_2 acting at once but for a shorter period

of time, and NO_2 acting later but for a longer period of time. However, Linn et al. (77) evaluated 24 normal and 19 asthmatic volunteers during intermittent light exercise for two hrs at 0.50 ppm NO_2 combined with 0.50 ppm SO_2 (normals) or 0.30 ppm SO_2 (asthmatics). These same authors conclude that there was no marked synergistic interaction between NO_2 and SO_2 as should be expected from these pollutants given the general negative finding in studies of each pollutant separately at these concentrations.

Epidemiological observations over a 13-year period involving adult mortality of two communities with widely different air pollution levels resulted in the hypothesis by Morris et al. (85) that smoking and air pollution are additive. However, Shephard (101) proposes that exposure to tobacco smoke could increase the toxicity of some air pollutants through a variety of mechanisms which ultimately could lead to synergistic effects. More recently, Shephard et al. (102) studied the interaction of O_3 and cigarette smoke in 32 volunteers (26 men, 6 women) during two hr exposures to intermittent light exercise. These same authors report little evidence that cigarette smoking effects the acute toxicity of O_3.

The interactive effects of PAN and CO (PANCO) have been studied during both submaximal and maximal exercise (49,95,96,97). At the low concentrations studied during either submaximal (50 ppm CO, 0.24 ppm PAN) or maximal exercise (50 ppm CO, 0.27 ppm PAN), these same authors report that exposure to these two pollutants either singly or in combination, did not cause adverse physiological effects during submaximal or maximal exercise. Thus, the interactive effects of PAN and CO would be considered additive.

Synergistic Interactions

In a study involving eight healthy men from Montreal during light intermittent cycling exercise while breathing 0.37 ppm O_3 combined with 0.37 ppm SO_2, Hazucha

and Bates (57) report that the combined effect of these two pollutants on pulmonary functions (FVC, $FEF_{50\%}$, $FEF_{25-75\%}$, $FEV_{1.0}$) was "much greater" than when either pollutant was breathed separately which suggests a synergistic effect. However, Bell et al. (19) were unable to confirm the synergistic effects of O_3 combined with SO_2 reported earlier by Hazucha and Bates (57) while utilizing a similar experimental protocol and evaluating nine volunteers (four Montreal subjects and five Los Angeles subjects). These same authors suggest three possible explanations for the differences between these two studies: (a) enhanced sensitivity of the Montreal volunteers, (b) adaptation of the Los Angeles residents particularly to O_3, and (c) the chemical formation of sulfur containing aerosols in the Montreal study causing greater effects. Additional studies of the combined exposure to O_3 and SO_2 at different concentrations (0.40 ppm O_3+0.40 ppm SO_2; 0.30 ppm O_3+1.0 ppm SO_2) during intermittent exercise also have not supported the suggested synergistic effect of these two pollutants (17,18,38). In a study involving 19 healthy human volunteers performing light intermittent cycling exercise for two hrs while breathing a mixture containing 0.37 ppm O_3, 0.37 ppm SO_2 and 100 $\mu g/m^3$ H_2SO_4, Kleinman et al. (67) indicated a 3.7 percent decline in $FEV_{1.0}$. These same authors suggest that the mixture produced a slight but not substantial change as O_3 alone should be expected to decrease $FEV_{1.0}$ by 2.8 percent under similar exposure conditions.

The interactive effects of O_3 (0.45 ppm) in combination with PAN (0.30 ppm) have been investigated during light intermittent cycling exercise in 10 healthy adult men (27). PAN exposure alone did not induce any changes in pulmonary functions. Decrements in pulmonary functions (FVC, $FEV_{1.0}$, $FEV_{2.0}$, $FEV_{3.0}$, $FEF_{25-75\%}$, IC, ERV and TLC) were 10% greater after combined exposure to O_3 and PAN than after O_3 exposure alone. While these findings suggest a synergistic effect between O_3 and PAN, additional studies are required before this hypothesis can be accepted.

Whereas Stacy et al. (109) indicate that sulfuric acid, sulfate aerosols $(NH_4)_2SO_4$, NH_4HSO_4) or nitrate aerosols (NH_4NO_3) do not interact synergistically with SO_2 or NO_2 during intermittent light exercise in man, McCafferty (81) after a careful review of the related literature suggests that the interactions between SO_2 and aerosols; and, certain other pollutants with sulfuric acid aerosols, the particulate sulfates and the particulate nitrates could be synergistic. The degree of synergism is thought to depend on the size of the aerosol with greater synergistic effects associated with breathing smaller particle aerosols. Unfortunately, the majority of studies that suggest a synergistic effect for the above pollutants involve small animal experimentation with even fewer studies evaluating human performance during submaximal exercise. Nevertheless, high concentrations of small particle size aerosols are known to exist in urban areas suggesting the need for further research on the interactive effects of these aerosols with certain other pollutants during exercise in man.

The interactive effects between the various pollutants during human performance of muscular exercise needs to be addressed in greater detail. Additional experiments should consider a wider range of concentrations between interactive pollutants, a variety of subject populations (normal vs. hyperractive, older vs. younger, etc.) at low, moderate and high exercise intensities.

POLLUTANT INTERACTIONS WITH THE ENVIRONMENT

As mentioned in the Introduction to this chapter, the combined effects of certain pollutants with the environmental extremes of heat, cold or altitude during physical exercise may result in additive and/or synergistic outcomes. While a number of investigations have been reported concerning the relative effects of environmental heat and adverse air quality, far fewer reports have been published on the interaction of high terrestrial altitude and air pollution. No studies have been reported on the effects of environmental cold and poor air quality.

Environmental Heat

Elevated concentrations of air pollution are often associated with excessive heat and humidity (32). Since excessive heat and humidity alone are related to increases in morbidity and mortality, it is not unreasonable to expect that with the addition of poor air quality morbidity and mortality rates could further increase (29). Certainly, human performance of submaximal or maximal exercise could be expected to suffer under the combined stresses of excessive heat, humidity and poor air quality.

Carbon monoxide and/or peroxyacetyl nitrate. While the atmospheric pollutants of CO and PAN, either singly or in combination (PANCO), have been evaluated during exercise-heat stress, the environmental conditions were limited to 30% rh at 25° C and 35° C (28,49,95,96,97). However, during the experiments both maximal and submaximal (~35% $\dot{V}O_2$max) exercise intensities were studied. Pollutant concentrations were limited to 50 ppm CO for all experiments with 0.24 ppm PAN for submaximal and 0.27 ppm PAN for maximal exercise. All subjects were described as healthy young or healthy middle-aged adult men. During submaximal exercise, no significant changes in physiological responses were reported while breathing CO, PAN or PANCO at 35° C (49,97). Nevertheless, subjective complaints, particularly for PAN and PANCO, were greater at 35° C. Gliner et al. (49) conclude that the pollutants CO, PAN or PANCO have relatively little effect on the physiological responses to submaximal exercise compared to increased ambient temperature. The $\dot{V}O_2$max was not altered during exposure to either CO, PAN or PANCO at 35° C (28,95). While breathing filtered air, exposure to this level of heat stress (35° C) was more effective in lowering $\dot{V}O_2$max (-4%) than exposure to either single pollutant or the two pollutants in combination at 25° C. Drinkwater et al. (28) conclude that heat stress was more effective in decreasing exercise capacity than any of these pollutant conditions. However, these same authors speculate that the combination of CO and heat stress may be important

in the more pronounced respiratory disturbances seen at this elevated ambient temperature compared to 25° C during maximal exercise. In conclusion, these authors suggest that heat stress w .s generally more effective in reducing human submaximal or maximal exercise performance than carbon monoxide and/r peroxyacetyl nitrate.

Ozone. Submaximal exercise performance (~40% $\dot{V}O_2max$) during O_3 exposure (0.50 ppm) has been evaluated a. four different environmental conditions (25° C, 45% rh; 31° C, 85% rh; 35° C, 40% rh; 40° C, 50% rh) for a two hr period in 14 healthy young men (41). A trend was found that indicated a greater impairment in pulmonary function during combined exposure to O_3 and heat stress. Decrements in pulmonary function after exposure to ozone and heat were greatest immediately following exercise. Reductions in VC and MCC were significant during the most extreme heat exposure (40° C, 50% rh) while exercise $\dot{V}_E$ was highest at this ambient temperature (plus O_3). Since heat and O_3 were not related to additional reductions in any other pulmonary flow variables compared to O_3 alone, these same authors suggest that some other mechanism(s) besides bronchoconstriction is related to the reported decrements in pulmonary function during exposure to these combined stresses. Folinsbee et al. (41) conclude that environmental heat stress may increase the response to O_3 suggesting a possible additive effect. In a study involving 10 aerobically trained young women performing moderately heavy exercise (66% $\dot{V}O_2max$) for one hr while breathing either filtered air, 0.15 or 0.30 ppm O_3 at 24 and 35° C, Gibbons and Adams (47) found that O_3 exposure combined with heat stress (35° C) produced an interactive effect on alveolar volume and respiratory rate with near significant interactions for FVC and $FVC_{1.0}$. In addition, there were more subjective complaints during O_3 exposure in the heat, and these combined stressors were more likely to prompt premature cessation of exercise. In a recent study involving 17 top-caliber endurance cyclists simulating competition conditions including submaximal cycling exercise (~70% $\dot{V}O_2max$) for one

hr followed by incremented exercise to exhaustion while breathing filtered air, 0.12 or 0.20 ppm O_3 in a warm environment (31° C). Gong et al. (50) report the threshold for significant impairment of exercise performance in this warm environment to be between 0.12 and 0.20 ppm O_3.

In addition to the adverse effects associated with poor air quality combined with elevated ambient temperature, extremes in the percent relative humidity are also thought to precipitate problems when associated with certain air pollutants (12,81). Low relative humidity is suggested to enhance the adverse health effects of O_3 while high relative humidity is thought to intensify the adverse effects of SO_2 and also probably NO_2 (12,81). It has been suggested that for SO_2 the high humidity accelerates catalytic oxidation of this pollutant to form aerosols which were more irritating than SO_2 itself (12,81). Arundel et al. (12) recommends an optimal range of 40 to 60% relative humidity to minimize the adverse effects of these pollutants. Nevertheless, the effects of extremes in percent relative humidity have not been systematically evaluated during human performance of submaximal or maximal exercise.

Future research is needed to more fully appraise the detrimental effects of heat stress and/or extremes in relative humidity for all of the air pollutants discussed during performance of muscular exercise. Encompassed in the research should be a range of pollutant concentrations, various subject populations and a wide range of exercise intensities.

Environmental Cold

In addition to many of the air pollutants, breathing cold air during exercise has been shown to induce a reflex bronchoconstriction, particularly prevalent in asthmatic individuals. The temperature and humidity of the inhaled cold air during exercise are critical in the resultant degree of bronchoconstriction. Unfortunately, no studies have directly evaluated the interactive effects of breathing cold polluted air and the

subsequent degree of airway obstruction during exercise. By inference, Pierson et al. (89) recently imply that breathing cold polluted air could adversely affect respiratory function and consequently athletic performance.

Exercise-induced asthma or bronchoconstriction has been reported to take place in about 12% of the population (62). Approximately 11% of the 1984 Olympic athletes were observed to have exercise-induced asthma or bronchoconstriction (113). Strenuous physical exercise of six to twelve min duration can result in airway obstruction with the symptoms being most pronounced five to ten min after cessation of exercise (107). Running is most likely to cause bronchoconstriction while swimming is least likely with cycling and walking being intermediate (107). Nasal breathing should help warm and humidity the air and lessen bronchoconstriction as will wearing a cold weather mask during exercise (107). However, cold air breathing during exercise should enhance or accentuate the bronchoconstriction response.

In a study of eight young asthmatic adults who performed heavy cycling exercise of short duration ($\bar{X}$=160.5±57.5(S.D.) W; 3.41±1.97(S.D.) min) while breathing air at either ambient (23 to 26° C) or sub-freezing (-11 to -15° C) temperatures, Strauss et al. (111) report a marked enhancement in the post-exercise bronchospastic response in these subjects after cold air inhalation relative to ambient air breathing. Ambient air inhalation also produced significant bronchoconstriction. Further, the effects of breathing cold air at rest were quite small as demonstrated from some of these experiments. Additional studies by this group suggest that the potentiating effects of cold air inhalation are local with the proximate stimulus related to cooling of the intrathoracic airways (24).

Increasing the humidity of ambient (22-25° C) or warm (36° C) air temperatures while performing heavy physical exercise of short duration has been shown to blunt the degree of airway obstruction in asthmatic children, adolescents and young adult

volunteers (8,110). Whether increasing the humidity of cold air during exercise would result in a significant lessening of the severe bronchoconstrictor response is open to question.

Physical exercise and cold air inhalation are thought to be synergistic in terms of the degree of exercise-induced bronchospasm. Strauss et al. (111) states that "less well known, but equally important, is the fact that short term exposure to low levels of atmospheric pollutants, like nitrogen dioxide, can increase the sensitivity of asthmatic patients to other bronchoconstrictor substances...". Might not these atmospheric pollutants also act synergistically with exercise and cold air inhalation to produce an even greater degree of exercise-induced bronchoconstriction?

High Altitude

As stated in the Introduction to this chapter, the effects of carbon monoxide at high altitude may be enhanced due to a greater degree of hypoxia. The hypoxemia associated with exercise at altitude is known to shift the oxygen dissociation curve to the right which permits more O_2 to be released to the tissues at a given blood PO_2 (114). However, CO shifts the oxygen dissociation curve to the left which makes tissue oxygen extraction more difficult. Collectively, the elevated COHb levels resulting from CO exposure and the lower O_2 tension of high altitude may produce additive effects (84).

Only a few studies have evaluated human physiological performance during exercise at high altitude while exposed to CO. In an early study involving three male subjects performing light cycle exercise at a simulated altitude of 4877 m (16,000 ft) while breathing relatively low concentrations of CO, Forbes et al. (45) reported an increased CO uptake associated with the observed hyperventilation at high altitude. However, when the values at sea level and simulated altitude were corrected to a standard ventilation rate of 10 L per min (ambient pressure), the differences in CO

uptake became insignificant. In another early investigation involving 10 adult men exposed for 25 min (5 min treadmill walking; 20 min rest) to three different simulated altitudes (2134, 3048, 4724 m) at COHb levels of 6 and 13 percent, Pitts and Pace (91) suggest a 1 percent increase in blood COHb was equivalent to a 102 m increase in altitude. These same authors indicate that this relationship was established for the altitude range of 2134 to 3048 m (7,000-10,000 ft) and for COHb levels up to 13 percent.

In more recent experiments involving 12 male adults (six smokers and six non-smokers) performing moderate intensity cycling exercise (53% $\dot{V}O_2$max) for 30 min at 3048 m (10,000 ft) while breathing CO (COHb=4.2%), Wagner et al. (114) state that this COHb concentration and level of altitude represented only marginal additional stressors to respiratory function. When compared to observations at either sea level, sea level while breathing CO, or altitude, the combination of hypoxic stressors (CO plus altitude) during exercise produced slightly greater increases in $\dot{V}_E$ and respiratory rate, but no difference in $\dot{V}O_2$ and TV. During low level CO exposure (COHb=5.1%) involving nine healthy male volunteers at an altitude of 1610 m (5282 ft), Weiser et al. (115) show that the impairments in maximal exercise capacity and exercise performance are of the same magnitude as observed at sea level. Since major reductions in $\dot{V}O_2$max occur at altitudes greater than about 1500 m with an approximate 3% decrement in $\dot{V}O_2$max per 300 m of additional ascent (87), it is not unreasonable to propose that low-level CO exposure may have a detrimental effect at higher altitudes ($\geq$2000 m).

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After an extensive review of the literature, Mitchell et al. (84) conclude that the current National Ambient Air Quality Standards derived at sea level for CO are

probably to lenient for altitudes of 1500 m or greater. Table 4 shows the CO exposure level (ppm) at sea level and 1500 m necessary to produce equal COHb concentrations of 1, 2 and 3 percent after 8-12 hrs. These same authors state that California is the only state to use 6 as compared to 9 ppm as an eight hr CO exposure standard for areas greater than 1500 m. In conclusion, additional research is necessary to fully understand the interactive effects of CO during altitude exposure. No definitive research has been reported concerning the potential adverse effects of the other pollutants during exercise performance at altitude.

SUMMARY

The various air pollutants have been classified as primary or secondary pollutants. Primary pollutants are emitted directly to the environment from their source and include carbon monoxide, sulfur oxides, nitrogen oxides and primary particulates. Secondary pollutants develop from interactions of primary pollutants and include ozone, peroxyacetyl nitrate and certain aerosols. Carbon monoxide does not appear to cause decrements in submaximal exercise performance in healthy individuals; however, cardiovascularly-impaired individuals appear to be at significant risk during submaximal exercise even at low carboxyhemoglobin levels. Maximal exercise performance for healthy individuals seems to be altered by breathing carbon monoxide with the critical concentration being 4.3% carboxyhemoglobin. The threshold level of sulfur dixoxide which effects submaximal exercise performance in healthy individuals is between 1.0 and 3.0 ppm while asthmatic individuals and possibly others with pulmonary hyperractivity are affected at a lower threshold concentration between 0.20 and 0.50 ppm. No studies have been reported concerning maximal exercise performance during sulfur dioxide exposure. Several studies suggest that healthy and asthmatic individuals may adapt to sulfur dioxide, but unfortunately no research has investigated adaptation to this pollutant during physical exercise. While no studies have been reported which

evaluate maximal exercise performance. nitrogen dioxide exposure does not appear to adversely affect submaximal exercise performance in healthy individuals. The physiological performance effects of breathing primary particulates have not been directly evaluated during exercise in man Ozone exposure does not appear to limit submaximal exercise performance at light to moderate exercise intensities. At heavy exercise intensities, ozone exposure can limit performance primarily due to severe respiratory discomfort and changes in pulmonary functions. While adaptation occurs after two to five consecutive days of exposure to ozone, this adaptation could eventually be harmful because of the associated suppression of the normal defense mechanisms. Submaximal and maximal exercise performance have not been altered dramatically during peroxyacetyl nitrate exposure at the concentrations tested. The sulfate aerosols, sulfuric acid and the nitrate aerosols elicit minimal adverse effects relative to some of the other pollutants when tested singly. The various pollutants may interact in three ways: (a) additively, (b) synergistically, or (c) antagonistically. Clear distinction between additive and synergistic interactions is frequently difficult and usually involves the specific pollutant concentrations. In general, ozone in combination with nitrogen dioxide represent an additive interaction, while ozone combined with peroxyacetyl nitrate seem to suggest synergistic effects. No pollutant interactions have been reported that are antagonistic. Human performance of submaximal or maximal exercise can be expected to suffer under the combined stresses of excessive heat, humidity and poor air quality. The interactive effects of breathing cold polluted air should increase the degree of exercise-induced bronchospasm and adversely effect exercise performance in susceptible individuals. The adverse effects of certain pollutants such as carbon monoxide may be enhanced at high altitude due to a greater degree of hypoxemia.

REFERENCES

1. Adams, W.C., W.M. Savin and A.E. Christo. Detection of ozone toxicity during continuous exercise via the effective dose concept. J. Appl. Physiol. 51:415-422, 1981.

2. Adams, W.C. and E.S. Schelegle. Ozone and high ventilation effects on pulmonary function and endurance performance. J. Appl. Physiol. 55:805-812, 1983.

3. Andersen, I., G.R. Lundqvist, P.L. Jensen and D.F. Proctor. Human response to controlled levels of sulfur dioxide. Arch. Environ. Health 28:31-39, 1974.

4. Anderson, E.W., R.J. Andelman, J.M. Strauch, N.J. Fortuin and J.H. Knelson. Effect of low-level carbon monoxide exposure on onset and duration of angina pectoris: a study in ten patients with ischemic heart disease. Ann. Intern. Med. 79:46-50, 1973.

5. Amdur, M.O., W.W. Melvin Jr. and P. Drinker. Effects of inhalation of sulfur dioxide in man. Lancet 1:758-759, 1953.

6. Amdur, M.O., L. Silverman and P. Drinker. Inhalation of sulfuric acid mist by human subjects. Arch. Ind. Hyg. 6:305-313, 1952.

7. American Medical Association. Carbon monoxide intoxication associated with use of a resurfacing machine at an ice-skating rink. JAMA 251:1016, 1984.

8. Amirav, I., R.J. Dowdeswell and M. Plit. Respiratory heat loss in exercise-induced asthma: measurement and clinical application. S. Afr. Med. J. 69:227-232, 1986.

9. Aronow, W.S. and J. Cassidy. Effect of carbon monoxide on maximal treadmill exercise: a study in normal persons. Ann. Intern. Med. 83:496-499, 1975.

10. Aronow, W.S., C.N. Harris, M.W. Isbell, S.N. Rokaw and B. Imparato. Effect of freeway travel on angina pectoris. Ann. Intern. Med. 77:669-676, 1972.

11. Aronow, W.S. and M.W. Isbell. Carbon monoxide effect on exercise-induced angina pectoris. Ann. Intern. Med. 79:392-395, 1973.

12. Arundel, R.A.V., E.M. Sterling, J.H. Biggin and T.D. Sterling. Indirect health effects of relative humidity in indoor environments. Environ. Health Perspect. 65:351-361, 1986.

13. Avol, E.L., M.P. Jones, R.M. Bailey, N.N. Chang, M.T. Kleinman, W.S. Linn, K.A. Bell and J.D. Hackney. Controlled exposures of human volunteers to sulfate aerosols. Am. Rev. Respir. Dis. 120:319-327, 1979.

14. Avol, E.L., W.S. Linn, D.A. Shamoo, T.G. Venet and J.D. Hackney. Acute respiratory effects of Los Angeles smog in continuously exercising adults. J. Air Pollut. Control Assoc. 33:1055-1060, 1983.

15. Avol, E.L., W.S. Linn, T.G. Venet, D.A. Shamoo and J.D. Hackney. Comparative respiratory effects of ozone and ambient oxidant pollution exposure during heavy exercise. J. Air Pollut. Control Assoc. 34:804-809, 1984.

16. Bedi, J.F., D.M. Drechsler-Parks and S.M. Horvath. Duration of increased pulmonary function sensitivity to an initial ozone exposure. Am. Ind. Hyg. Assoc. J. 46:731-734, 1985.

17. Bedi, J.F., L.J. Folinsbee, S.M. Horvath and R.S. Ebsenstein. Human exposure to sulfur dioxide and ozone: absence of a synergistic effect. Arch. Environ. Health 34:233-239, 1979.

18. Bedi, J.F., S.M. Horvath and L.J. Folinsbee. Human exposure to sulfur dioxide and ozone in a high temperature-humidity environment. Am. Ind. Hyg. Assoc. J. 43:26-30, 1982.

19. Bell, K.A., W.S. Linn, M. Hazucha, J.D. Hackney and D.V. Bates. Respiratory effects of exposure to ozone plus sulfur dioxide in Southern Californians and Eastern Canadians. Am. Ind. Hyg. Assoc. J. 38:696-706, 1977.

20. Bromberg, P.A. and M.J. Hazucha. Is "adaptation" to ozone protective? Am. Rev. Respir. Dis. 125:489-490, 1982.

21. Comroe, J., R. Forster, A. Dubois, W. Briscoe and E. Carlsen. The Lung: Clinical Physiology and Pulmonary Function Tests. Chicago: Yearbook Medical Publishers, 1962.

22. Corn, M. and G. Burton. The irritant potential of pollutants in the atmosphere. Arch. Environ. Health 14:54-61, 1967.

23. Dautrebande, L., W.C. Alford, B. Highman, R. Downing and F.L. Weaver. Studies on aerosols V.: effect of dust and pneumodilating aerosols on lung volume and type of respiration in man. J. Appl. Physiol. 1:339-349, 1948.

24. Deal Jr., E.C., E.R. McFadden Jr., R.H. Ingram Jr. and J.J. Jaeger. Effects of atropine on potentiation of exercise-induced bronchospasm by cold air. J. Appl. Physiol. 45:238-243, 1978.

25. DeLucia, A.J. and W.C. Adams. Effects of O_3 inhalation during exercise on pulmonary function and blood biochemistry. J. Appl. Physiol. 43:75-81, 1977.

26. Dimeo, M.J., M.G. Glenn, M.J. Holtzman, J.R. Sheller, J.A. Nadel and H.A. Boushey. Threshold concentration of ozone causing an increase in bronchial reactivity in humans and adaptation with repeated exposures. Am. Rev. Respir. Dis. 124:245-248, 1981.

27. Drechsler-Parks, D.M., J.F. Bedi and S.M. Horvath. Interaction of peroxyacetyl nitrate and ozone on pulmonary functions. Am. Rev. Respir. Dis. 130:1033-1037, 1984.

28. Drinkwater, B.L., P.B. Raven, S.M. Horvath, J.A. Gliner, R.O. Ruhling, N.W. Bolduan and S. Taguchi. Air pollution, exercise and heat stress. Arch. Environ. Health 28:177-181, 1974.

29. Driscoll, D.M. Base lines for measuring adverse effects of air pollution: some evidence for weather effects on mortality. Environ. Res. 4:233-242, 1971.

30. Dubois, A.B. and L. Dautrebande. Acute effects of breathing inert dust particles and of carbachol aerosol on the mechanical characteristics of the lungs in man: changes in response after inhaling sympathomimetic aerosols. J. Clin. Invest. 37:1746-1755, 1958.

31. Ekblom, B. and R. Huot. Response to submaximal and maximal exercise at different levels of carboxyhemoglobin. Acta Physiol. Scand. 86:474-482, 1972.

32. Ellis, F.P. Mortality from heat illness and heat-aggravated illness in the United States. Environ. Res. 5:1-58, 1972.

33. Farrell, B.P., H.D. Kerr, T.J. Kulle, L.R. Sauder and J.L. Young. Adaptation in human subjects to the effects of inhaled ozone after repeated exposure. Am. Rev. Respir. Dis. 119:725-730, 1979.

34. Folinsbee, L.J. Effects of ozone exposure on lung function in man: a review. Rev. Environ. Health 3:211-240, 1981.

35. Folinsbee, L.J., J.F. Bedi, J.A. Gliner and S.M. Horvath. Concentration dependence of pulmonary function adaptation to ozone. In The Biomedical Effects of Ozone and Related Photochemical Oxidants. Edited by M.A. Mehlman, S.D. Lee and M.G. Mustafa. Princeton Junction N.J.: Princeton Scientific Publishers, Inc., pp. 175-187, 1983.

36. Folinsbee, L.J., J.F. Bedi and S.M. Horvath. Combined effects of ozone and nitrogen dioxide on respiratory function in man. Am. Ind. Hyg. Assoc. J. 42:534-541, 1981.

37. Folinsbee, L.J., J.F. Bedi and S.M. Horvath. Pulmonary function after 1 h continuous heavy exercise in 0.21 ppm ozone. J. Appl. Physiol. 57:984-988, 1984.

38. Folinsbee, L.J., J.F. Bedi and S.M. Horvath. Pulmonary response to threshold levels of sulfur dioxide (1.0 ppm) and ozone (0.3 ppm). J. Appl. Physiol. 58:1783-1787, 1985.

39. Folinsbee, L.J., J.F. Bedi and S.M. Horvath. Respiratory responses in humans repeatedly exposed to low concentrations of ozone. Am. Rev. Respir. Dis. 121:431-439, 1980.

40. Folinsbee, L.J., S.M. Horvath, J.F. Bedi and J.C. Delehunt. Effect of 0.62 ppm NO_2 on cardiopulmonary function in young male nonsmokers. Environ. Res. 15:199-205, 1978.

41. Folinsbee, L.J., S.M. Horvath, P.B. Raven, J.F. Bedi, A.R. Morton, B.L. Drinkwater, N.W. Bolduan and J.A. Gliner. Influence of exercise and heat stress on pulmonary function during ozone exposure. J. Appl. Physiol. 43:409-413, 1977.

42. Folinsbee, L.J., F. Silverman and R.J. Shephard. Decrease of maximum work performance following ozone exposure. J. Appl. Physiol. 42:531-536, 1977.

43. Folinsbee, L.J., F. Silverman and R.J. Shephard. Exercise responses following ozone exposure. J. Appl. Physiol. 38:996-1001, 1975.

44. Folinsbee, L.J. and P.B. Raven. Exercise and air pollution. J. Sports Sci. 2:57-75, 1984.

45. Forbes, W.H., F. Sargent and F.J.W. Roughton. The rate of carbon monoxide uptake by normal men. Am. J. Physiol. 143:594-608, 1945.

46. Foxcroft, W.J. and W.C. Adams. Effects of ozone exposure on four consecutive days on work performance and $\dot{V}O_{2max}$. J. Appl. Physiol. 61:960-966, 1986.

47. Gibbons, S.I. and W.C. Adams. Combined effects of ozone exposure and ambient heat on exercising females. J. Appl. Physiol. 57:450-456, 1984.

48. Gliner, J.A., S.M. Horvath and L.J. Folinsbee. Preexposure to low ozone concentrations does not diminish the pulmonary function response on exposure to higher ozone concentrations. Am. Rev. Respir. Dis. 127:51-55, 1983.

49. Gliner, J.A., P.B. Raven, S.M. Horvath, B.L. Drinkwater and J.C. Sutton. Man's physiologic response to long-term work during thermal and pollutant stress. J. Appl. Physiol. 39:628-632, 1975.

50. Gong Jr., H., P.W. Bradley, M.S. Simmons and D.P. Tashkin. Impaired exercise performance and pulmonary function in elite cyclists during low-level ozone exposure in a hot environment. Am. Rev. Respir. Dis. 134:726-733, 1986.

51. Hackney, J.D. Relationship between air pollution and cardiovascular disease: a review. In Clinical Implications of Air Pollution Research. Edited by A.J. Finkel and W.C. Duel. Acton, MA: Publishing Sciences Group, Inc., pp.89-106, 1976.

52. Hackney, J.D., W.S. Linn, S.K. Karuza, R.D. Buckley, D.C. Law, D.V. Bates, M. Hazucha, L.D. Pengelly and F. Silverman. Effects of ozone exposure in Canadians and Southern Californians: evidence for adaptation? Arch. Environ. Health 32:110-116, 1977

53. Hackney, J.D., W.S. Linn, D.C. Law, S.K. Karuza, H. Greenberg, R.D. Buckley and E.E. Pedersen. Experimental studies on human health effects of air pollutants III: two-hour exposure to ozone alone and in combination with other pollutant gases. Arch. Environ. Health 30:385-390, 1975.

54. Hackney, J.D., W.S. Linn, J.G. Mohler and C.R. Collier. Adaptation to short-term respiratory effects of ozone in men exposed repeatedly. J. Appl. Physiol. 43:82-85, 1977.

55. Hackney, J.D., W.S. Linn, J.G. Mohler, E.E. Pedersen, P. Breisacher and A. Russo. Experimental studies on human health effects of air pollutants II: four-hour exposure to ozone alone and in combination with other pollutant gases. Arch. Environ. Health 30:379-384, 1975.

56. Hackney, J.D., F.C. Thiede, W.S. Linn, E.E. Pedersen, C.E. Spier, D.C. Law and D.A. Fischer. Experimental studies on human health effects of air pollutants IV:

short-term physiological and clinical effects of nitrogen dioxide exposure. Arch. Environ. Health 33:176-181, 1978.

57. Hazucha, M. and D.V. Bates. Combined effect of ozone and sulphur dioxide on human pulmonary function. Nature 257:50-51, 1975.

58. Horvath, S.M. Impact of air quality in exercise performance. In Exercise and Sport Sciences Reviews. Edited by D.I. Miller. Philadelphia: The Franklin Institute Press, pp. 265-296, 1981.

59. Horvath, S.M., J.A. Gliner and L.J. Folinsbee. Adaptation to ozone: duration of effect. Am. Rev. Respir. Dis. 123:496-499, 1981.

60. Horvath, S.M., J.A. Gliner and J.A. Matsen-Twisdale. Pulmonary function and maximum exercise responses following acute ozone exposure. Aviat. Space Environ. Med. 50:901-905, 1979.

61. Horvath, S.M., P.B. Raven, T.E. Dahms and D.J. Gray. Maximal aerobic capacity at different levels of carboxyhemoglobin. J. Appl. Physiol. 38:300-303, 1975.

62. Katz, R.M. Prevention with and without the use of medications for exercise-induced asthma. Med. Sci. Sports Exerc. 18:331-333, 1986.

63. Kelly, F.J. and W.E. Gill. Ozone poisoning. Arch. Environ. Health 10:517-519, 1965.

64. Kilburn, K. Cilia and mucous transport as determinants of the response of lung to air pollutants. Arch. Environ. Health 14:77-91, 1967.

65. Kirkpatrick, M.B., D. Sheppard, J.A. Nadel and H.A. Boushey. Effect of the oronasal breathing route on sulfur dioxide-induced bronchoconstriction in exercising asthmatic subjects. Am. Rev. Respir. Dis. 125:627-631, 1982.

66. Kleinfeld, M. and C.P. Giel. Clinical manifestations of ozone poisoning: report of a new source of exposure. Am. J. Med. Sci. 231:638-643, 1956.

67. Kleinman, M.T., R.M. Bailey, Y.C. Chang, K.W. Clark, M.P. Jones, W.S. Linn and J.D. Hackney. Exposures of human volunteers to a controlled atmospheric mixture of ozone, sulfur dioxide and sulfuric acid. Am. Ind. Hyg. Assoc. J. 42:61-69, 1981.

68. Kleinman, M.T., W.S. Linn, R.M. Bailey, M.P. Jones and J.D. Hackney. Effect of ammonium nitrate aerosol on human respiratory function and symptoms. Environ. Res. 21:317-326, 1980.

69. Koenig, J.Q., W.E. Pierson and R. Frank. Acute effects of inhaled SO_2 plus NaCl droplet aerosol on pulmonary function in asthmatic adolescents. Environ. Res. 22:145-153, 1980.

70. Koenig, J.Q., W.E. Pierson, M. Horike and R. Frank. Effects of SO_2 plus NaCl aerosol combined with moderate exercise on pulmonary function in asthmatic adolescents. Environ. Res. 25:340-348, 1981.

71. Kreisman, H., C.A. Mitchell, H.R. Hosein and A. Bouhuys. Effect of low concentrations of sulfur dioxide on respiratory function in man. Lung 154:25-34, 1976.

72. LaBelle, C.W. and H. Brieger. Synergistic effects of aerosols II: effects on rate of clearance from the lung. Arch. Indus. Health 20:100-105, 1959.

73. Lauritzen, S.K. and W.C. Adams. Ozone inhalation effects consequent to continuous exercise in females: comparison to males. J. Appl. Physiol. 59:1601-1606, 1985.

74. Leikauf, G., D.B. Yeates, K.A. Wales, D. Spektor, R.E. Albert and M. Lippmann. Effects of sulfuric acid aerosol on respiratory mechanics and mucociliary particle clearance in healthy nonsmoking adults. Am. Ind. Hyg. Assoc. J. 42:273-282, 1981.

75. Linn, W.S., M.P. Jones, E.A. Bachmayer, K.W. Clark, S.K. Karuza and J.D. Hackney. Effect of low-level exposure to ozone on arterial oxygenation in humans. Am. Rev. Respir. Dis. 119:731-740, 1979.

76. Linn, W.S., M.P. Jones, E.A. Bachmayer, C.E. Spier, S.F. Mazur, E.L. Avol and J.D. Hackney. Short-term respiratory effects of polluted ambient air: a laboratory study of volunteers in a high-oxidant community. Am. Rev. Respir. Dis. 121:243-252, 1980.

77. Linn, W.S., M.P. Jones, R.M. Bailey, M.T. Kleinman, C.E. Spier, D.A. Fischer and J.D. Hackney. Respiratory effects of mixed nitrogen dioxide and sulfur dioxide in human volunteers under simulated ambient exposure conditions. Environ. Res. 22:431-438, 1980.

78. Linn, W.S., D.A. Medway, U.T. Anzar, L.M. Valencia, C.E. Spier, F.S.D. Tsao, D.A. Fischer and J.D. Hackney. Persistence of adaptation to ozone in volunteers exposed repeatedly for six weeks. Am. Rev. Respir. Dis. 125:491-495, 1982.

79. Linn, W.S., T.G. Venet, D.A. Shamoo, L.M. Valencia, U.T. Anzar, C.E. Spier and J.D. Hackney. Respiratory effects of sulfur dioxide in heavily exercising asthmatics. Am. Rev. Respir. Dis. 127:278-283, 1983.

80. Lowry, T. and L.M. Schuman. "Silo-filler's disease"-a syndrome caused by nitrogen dioxide. JAMA 162:153-160, 1956.

81. McCafferty, W.B. Air Pollution and Athletic Performance. Springfield, IL: Charles C. Thomas Publisher, 1981

82. McDonnell, W.F., R.S. Chapman, M.W. Leigh, G.L. Strope and A.M. Collier. Respiratory responses of vigorously exercising children to 0.12 ppm ozone exposure. Am. Rev. Respir. Dis. 132:875-879, 1985.

83. McDonnell, W.F., D.H. Horstman, M.J. Hazucha, E. Seal, Jr., E.D. Haak, S.A. Salaam and D.E. House. Pulmonary effects of ozone exposure during exercise: dose-response characteristics. J. Appl. Physiol. 54:1345-1352, 1983.

84. Mitchell, R.S., F.N. Judson, T.S. Moulding, P. Weiser, L.L. Brock, D.L. Keible and J. Pollard. Health effects of urban air pollution: special consideration of areas at 1,500 m and above. JAMA 242:1163-1168, 1979.

85. Morris, S.C., M.A. Shapiro and J.H. Waller. Adult mortality in two communities with widely different air pollution levels. Arch. Environ. Health 31:248-254, 1976.

86. Nadel, J.A. and J.H. Comroe, Jr. Acute effects of inhalation of cigarette smoke on airway conductance. J. Appl. Physiol. 16:713-716, 1961.

87. Pandolf, K.B. Importance of environmental factors for exercise testing and exercise prescription. In Exercise Testing and Exercise Prescription for Special Cases - Theoretical Basis and Clinical Application.' Edited by J.S. Skinner. Philiadelphia, PA: Lea & Febiger, pp. 77-98, 1987.

88. Pierson, W.E., D.S. Covert and J.Q. Koenig. Air pollutants, bronchial hyperreactivity, and exercise. J. Allergy Clin. Immunol. 73:717-721, 1984.

89. Pierson, W.E., D.S. Covert, J.Q. Koenig, T. Namekata and Y.S. Kim. Implications of air pollution effects on athletic performance. Med. Sci. Sports Exerc. 18:322-327, 1986.

90. Pirnay, F., J. Dujardin, R. Deroanne and J.M. Petit. Muscular exercise during intoxication by carbon monoxide. J. Appl. Physiol. 31:573-575, 1971.

91. Pitts, G.C. and N. Pace. The effect of blood carboxyhemoglobin concentration on hypoxia tolerance. Am. J. Physiol. 148:139-151, 1947.

92. Posin, C., K. Clark, M.P. Jones, J.V. Patterson, R.D. Buckley and J.D. Hackney. Nitrogen dioxide inhalation and human blood biochemistry. Arch. Environ. Health 33:318-324, 1978.

93. Raven, P.B. Air pollution and physical activity. Sports Med. Dig. 6:1-3, 1984.

94. Raven, P.B. Heat and air pollution: the cardiac patient. In Heart Disease and Rehabilitation. Edited by M.L. Pollock and D.H. Schmidt. Boston: Houghton and Mifflin Book Company, pp. 563-586, 1979.

95. Raven, P.B., B.L. Drinkwater, S.M. Horvath, R.O. Ruhling, J.A. Gliner, J.C. Sutton and N.W. Bolduan. Age, smoking habits, heat stress, and their interactive effects with carbon monoxide and peroxyacetylnitrate on man's aerobic power. Int. J. Biometeor. 18:222-232, 1974.

96. Raven, P.B., B.L. Drinkwater, R.O. Ruhling, N. Bolduan, S. Taguchi, J. Gliner and S.M. Horvath. Effect of carbon monoxide and peroxyacetyl nitrate on man's maximal aerobic capacity. J. Appl. Physiol. 36:288-293, 1974.

97. Raven, P.B., J.A. Gliner and J.C. Sutton. Dynamic lung function changes following long-term work in polluted environments. Environ. Res. 12:18-25, 1976.

98. Sackner, M.A., D. Ford, R. Fernandez, J. Cipley, D. Perez, M. Kwoka, M. Reinhart, E.D. Michaelson, R. Schreck and A. Wanner. Effects of sulfuric acid

aerosol on cardiopulmonary function of dogs, sheep, and humans. Am. Rev. Respir. Dis. 118:497-510, 1978.

99. Savin, W.M. and W.C. Adams. Effects of ozone inhalation on work performance and $\dot{V}O_{2max}$. J. Appl. Physiol. 46:309-314, 1979.

100. Schelegle, E.S. and W.C. Adams. Reduced exercise time in competitive simulations consequent to low level ozone exposure. Med. Sci. Sports Exerc. 18:408-414, 1986.

101. Shephard, R. Cigarette smoking and reactions to air pollutants. Can. Med. Assoc. J. 118:379-381, 1978.

102. Shephard, R.J., B. Urch, F. Silverman and P.N.J. Corey. Interaction of ozone and cigarette smoke exposure. Environ. Res. 31:125-137, 1983.

103. Sheppard, D., J. Epstein, R.A. Bethel, J.A. Nadel and H.A. Boushey. Tolerance to sulfur dioxide-induced bronchoconstriction in subjects with asthma. Environ. Res. 30:412-419, 1983.

104. Sheppard, D., A. Saisho, J.A. Nadel and H.A. Boushey. Exercise increases sulfur dioxide-induced bronchoconstriction in asthmatic subjects. Am. Rev. Respir. Dis. 123:486-491, 1981.

105. Sheppard, D., W.S. Wong, C.F. Uehara, J.A. Nadel and H.A. Boushey. Lower threshold and greater bronchomotor responsiveness of asthmatic subjects to sulfur dioxide. Am. Rev. Respir. Dis. 122:873-878, 1980

106. Sim, V.M. and R.E. Pattle. Effect of possible smog irritants on human subjects. JAMA 165:1908-1913, 1957.

107. Sly, R.M. History of exercise-induced asthma. Med. Sci. Sports Exerc. 18:314-317, 1986.

108. Snell, R.E. and P.C. Luchsinger. Effects of sulfur dioxide on expiratory flow rates and total respiratory resistance in normal human subjects. Arch. Environ. Health 18:693-698, 1969.

109. Stacy, R.W., E. Seal, Jr., D.E. House, J. Green, L.J. Roger and L. Raggio. A survey of effects of gaseous and aerosol pollutants on pulmonary function of normal males. Arch. Environ. Health 38:104-115, 1983.

110. Strauss, R.H., E.R. McFadden, Jr., R.H. Ingram, Jr., E.C. Deal, Jr. and J.J. Jaeger. Influence of heat and humidity on the airway obstruction induced by exercise in asthma. J. Clin. Invest. 61:433-440, 1978.

111. Strauss, R.H., E.R. McFadden, Jr., R.H. Ingram, Jr. and J.J. Jaeger. Enhancement of exercise-induced asthma by cold air. N. Engl. J. Med. 297:743-747, 1977.

112. Vogel, J.A. and M.A. Gleser. Effect of carbon monoxide on oxygen transport during exercise. J. Appl. Physiol. 32:234-239, 1972.

113. Voy, R.O. The U.S. Olympic Committee experience with exercise-induced bronchospasm, 1984. Med. Sci. Sports Exerc. 18:328-330, 1986.

114. Wagner, J.A., S.M. Horvath, G.M. Andrew, W.H. Cottle and J.F. Bedi. Hypoxia, smoking history, and exercise. Aviat. Space Environ. Med. 49:785-791, 1978.

115. Weiser, P.C., C.G. Morrill, D.W. Dickey, T.L. Kurt and G.J.A. Cropp. Effects of low-level carbon monoxide exposure on the adaptation of healthy young men to aerobic work at an altitude of 1,610 meters. In Environmental Stress: Individual Human Adaptations. Edited by L.J. Folinsbee, J.A. Wagner, J.F. Borgia, B.L. Drinkwater, J.A. Gliner and J.F. Bedi. New York: Academic Press, Inc., pp. 101-110, 1978.

116. West, J.B. Respiratory Physiology - the Essentials. Baltimore: Williams and Wilkins, 1979.

117. Widdicombe, J.G., D.C. Kent and J.A. Nadel. Mechanism of bronchoconstriction during inhalation of dust. J. Appl. Physiol. 17:613-616, 1962.

118. Wolff, E., M. Dolovich, C. Rossman and M. Newhouse. Sulfur dioxide and tracheobronchial clearance in man. Arch. Environ. Health 30:521-527, 1975.

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Table 1. Possible Adverse Effects of Air Pollution on Health With Air Pollution Index Greater than 100 ('Unhealthy').

Pollutant	Averaging Time(hr)	Primary NAAQS	Explanation Given
CO	8	9 ppm	Impaired exercise tolerance in persons with cardiovascular disease
	1	35 ppm	Decreased physical performance in normal adults
O_3	1	0.12 ppm	Aggravation of chronic lung disease and asthma
			Irritation of the respiratory tract in healthy adults
			Decreased visual acuity; eye irritation
			Decreased cardiopulmonary reserve in healthy subjects
SO_2	24	0.14 ppm	Increased hospital admissions for respiratory illness in elderly patients with related illness
TSP	24	$150\mu g/m^3$	Aggravation of chronic lung disease and asthma
			Aggravation of cardiorespiratory disease symptoms in elderly patients with heart or chronic lung disease
			Increased cough, chest discomfort and restricted activity

CO = carbon monoxide, O_3 = ozone, SO_2 = sulfur dioxide, TSP = total suspended particulates.

Averaging time defines the specific time in hours which the specific pollutant being monitored is averaged. For example, the level of CO fluctuates over an 8-hour period from 0 ppm to above 100 ppm. If the 8-hour average is greater than 9 ppm, then the level has exceeded the primary National Average Air Quality Standards (NAAQS).

Source Environmental Protection Agency.

Table 2. Comparison of PSI Values with Pollutant Concentrations and Descriptor Words.

		Pollutant Levels					
Index Value	Air Quality Level	TSP (24-hr), $\mu g/m^3$	SO_2 (24-hr), $\mu g/m^3$	CO (8-hr), $\mu g/m^3$	O_3 (1-hr), $\mu g/m^3$	NO_2 (1-hr), $\mu g/m^3$	Health Effect Descriptor
500	Significant Harm	600	2620	57.5	1200	3750	
400	Emergency	500	2100	46.0	1000	3000	Hazardous
300	Warning	420	1600	34.0	800	2260	Very Unhealthful
200	Alert	350	800	17.0	400	1130	Unhealthful
100	NAAQS	150	365	10.0	235	*	Moderate
50	50% of NAAQS	50	80	5.0	118	*	Good
0		0	0	0.0	0	*	

* No index values reported at concentration levels below those specified by 'alert level' criteria.

To convert $\mu g/m^3$ = ppm x molecular weight / 0.024.

Source: Environmental Protection Agency.

Table 3 Effects of Air Pollutants on Exercise Performance of Normal Individuals.

Air Pollutant Exercise Intensity	Performance Decrement	No Effect	Selected References
CO			
- Submaximal Exercise		X	Drinkwater et al. 1974; Ekblom and Huot, 1972; Gliner et al. 1975; Horvath et al. 1975; Pirnay et al. 1971; Raven et al. 1974; Vogel and Gleser, 1972.
- Maximal Exercise	X		
SO_2			
- Submaximal Exercise	?		Bedi et al. 1979; Bell et al. 1977; Folinsbee et al. 1985; Huzacha and Bates, 1975; Kreisman et al. 1976; Snell and Luchsinger, 1969; Stacy et al. 1983; Raven et al. 1979; Wolff et al. 1975.
- Maximal Exercise	?		
NO_2			
- Submaximal Exercise		X	Folinsbee et al. 1978; Hackney et al. 1978; Horvath and Folinsbee, 1978; Posin et al. 1978; Raven, 1979; Stacy et al. 1983.
- Maximal Exercise	?		
Particulates			
- Submaximal Exercise	?		DuBois and Dautrebande, 1958; Nadel and Comroe, 1961; Widdicombe et al. 1962.
- Maximal Exercise	?		
O_3			
- Submaximal Exercise		X	Adams et al. 1981; Adams and Schelegle, 1983; Bedi et al. 1979; Bedi et al. 1982; Bell et al. 1977; DeLucia and Adams, 1977; Folinsbee et al. 1975; Folinsbee et al. 1977; Folinsbee et al. 1984; Folinsbee et al. 1985; Hazucha and Bates, 1975; Horvath et al. 1979; Lauritzen and Adams, 1985; Linn et al. 1979; McDonnell et al. 1983; McDonnell et al. 1985; Savin and Adams, 1979; Schelegle and Adams, 1986; Stacy et al. 1983.
- Maximal Exercise	?		
PAN			
- Submaximal Exercise		X	Drinkwater et al. 1974; Gliner et al. 1975; Raven et al. 1974; Raven et al. 1976; Raven, 1979.
- Maximal Exercise	?		
Aerosols			
- Submaximal Exercise	?		Amdur et al. 1952; Avol et al. 1979; Kleinman et al. 1980; Koenig et al. 1980; Koenig et al. 1981; Leikauf et al. 1981; Sackner et al. 1983; Sim and Pattle, 1957; Stacy et al. 1983.
- Maximal Exercise	?		

Table 4. Effect of High Altitude on Carboxyhemoglobin (COHb) Concentrations after Carbon Monoxide (CO) Exposure for Eight to Twelve Hours.

COHb(%)	CO Exposure (ppm) Sea Level	1500 m
1.0	9	6
1.5	12	8
2.0	15	10

FIGURE LEGENDS

Figure 1. Lung volumes and lung capacities. Reprinted with permission from McCafferty (81).

Figure 2. Carbon monoxide (ppm) and ozone (ppm) observations from the Los Angeles area which illustrate the daily and seasonal fluctuations. Modified from a version originally published by McCafferty (81).

Figure 3. Relationship between the percent carboxyhemoglobin and the percent decrement in maximal oxygen uptake ($\dot{V}O_2max$) for smokers and non-smokers. Reprinted with permission from Horvath (58).

Figure 4. Differences in the percent increase in pulmonary flow resistance over time for healthy individuals breathing sulfur dioxide (SO_2) orally or nasally. Modified from a version published by McCafferty (81).

Figure 5. Number of days necessary to produce adaptation to ozone (O_3) for 24 individuals at 0.42 ppm O_3 for two hr exposures during five consecutive days. The two subjects indicated on day 6 never demonstrated adaptation. Reprinted with permission from Folinsbee et al. (35).

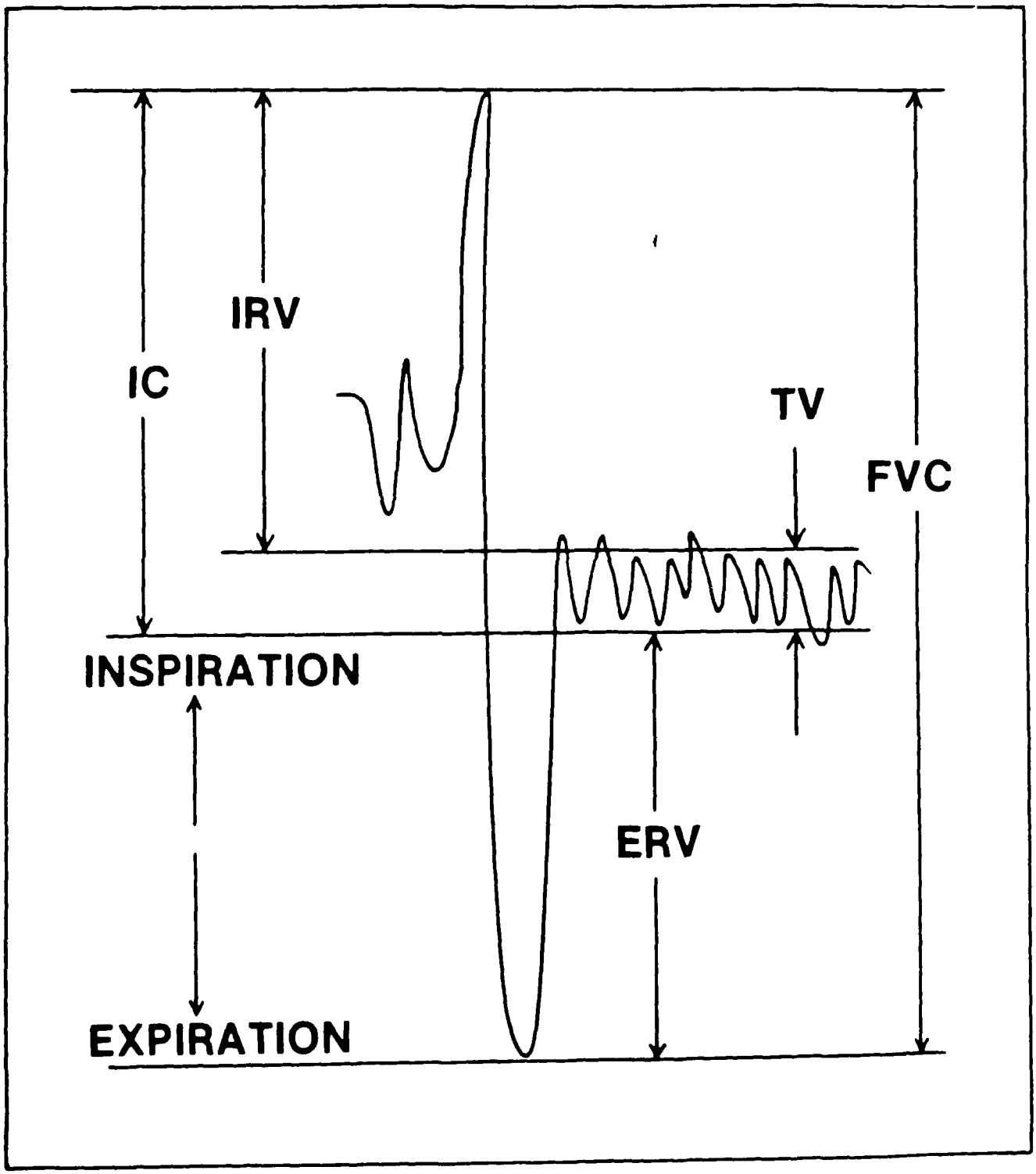

Fig. 1

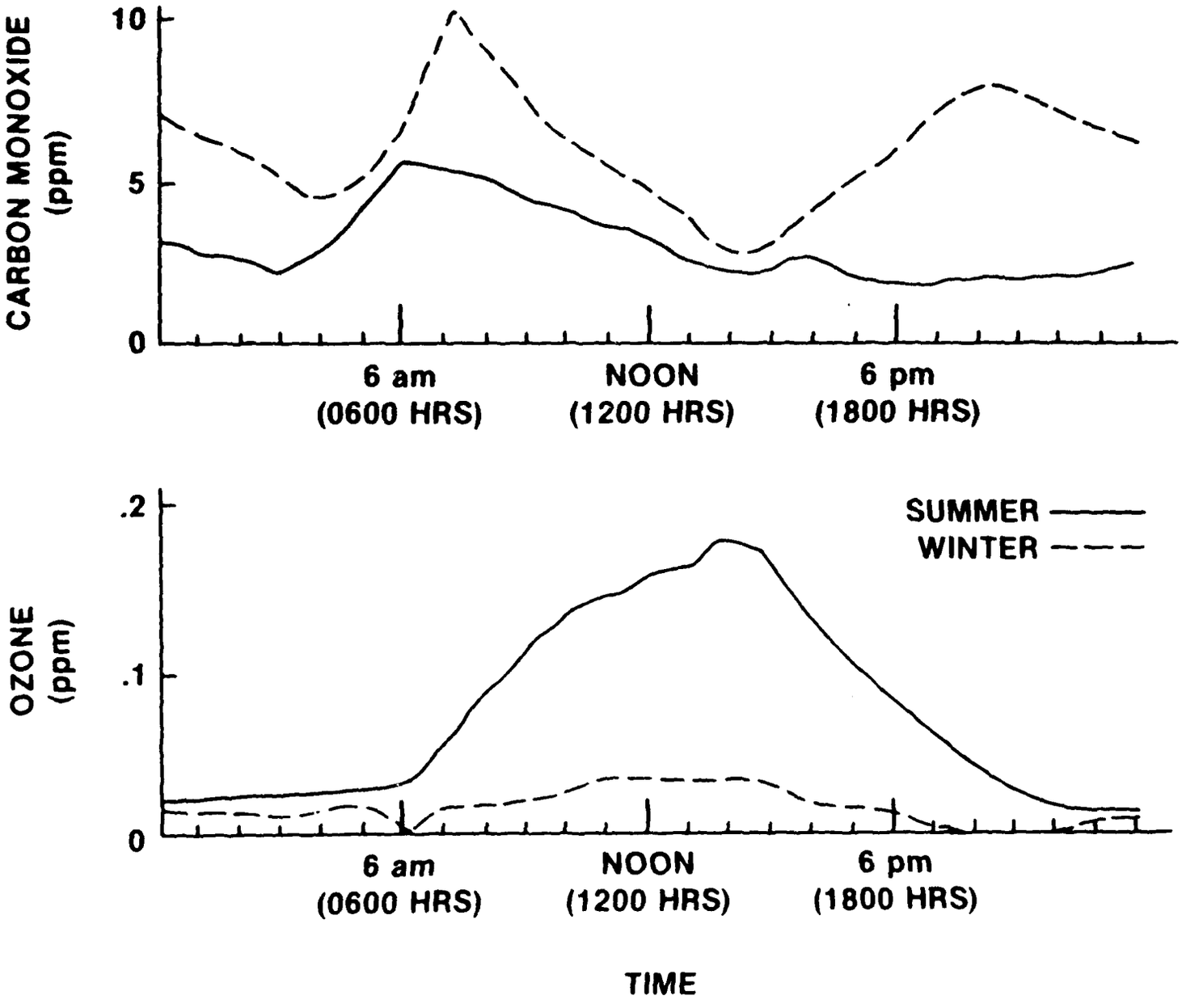
CARBON MONOXIDE (ppm)
10
5
0
6 am (0600 HRS)
NOON (1200 HRS)
6 pm (1800 HRS)
OZONE (ppm)
.2
.1
0
SUMMER
WINTER
6 am (0600 HRS)
NOON (1200 HRS)
6 pm (1800 HRS)
TIME

Fig. 2

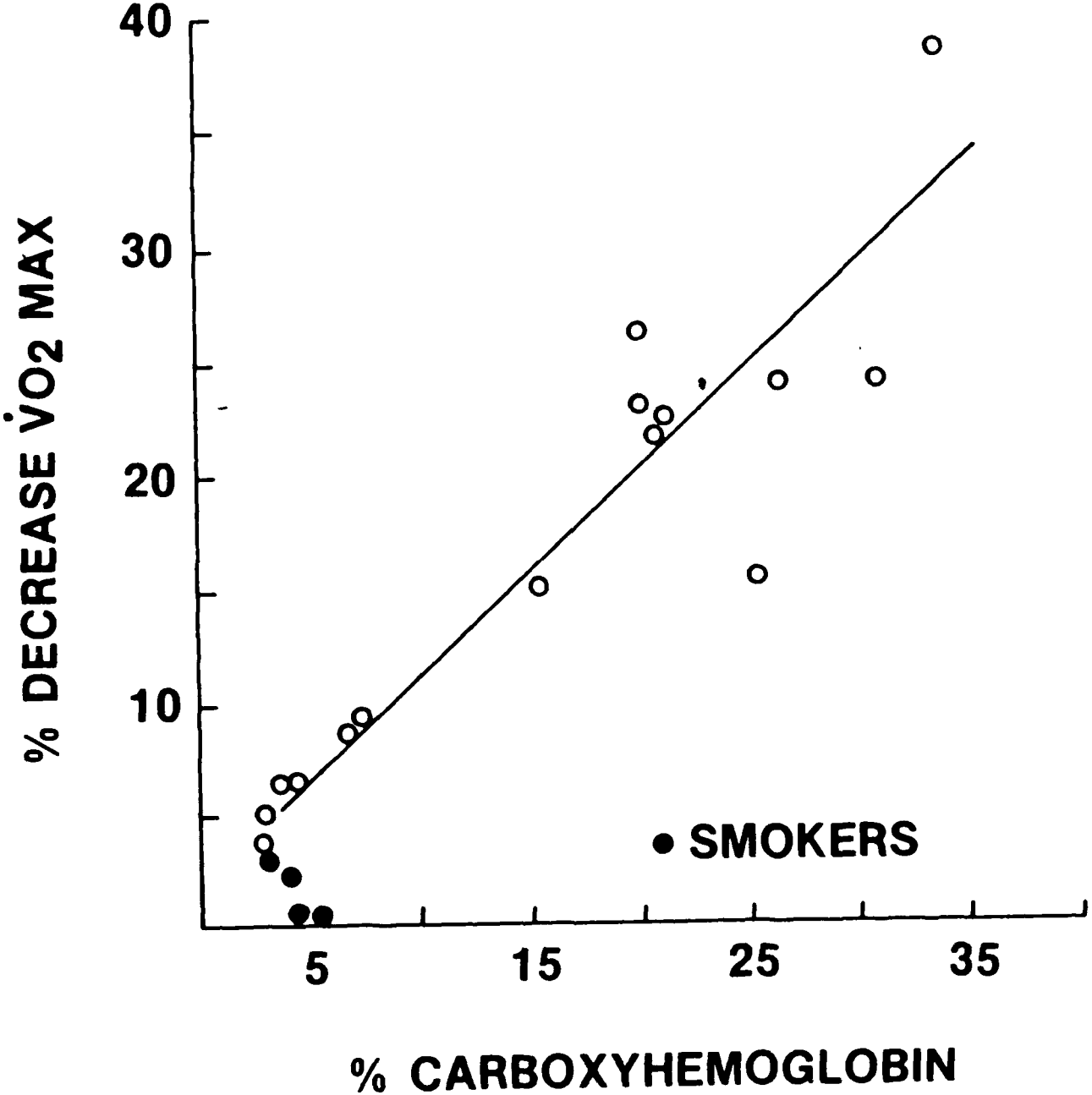
40
30
20
10
% DECREASE $\dot{V}O_2$ MAX
• SMOKERS
5
15
25
35
% CARBOXYHEMOGLOBIN

Fig. 3

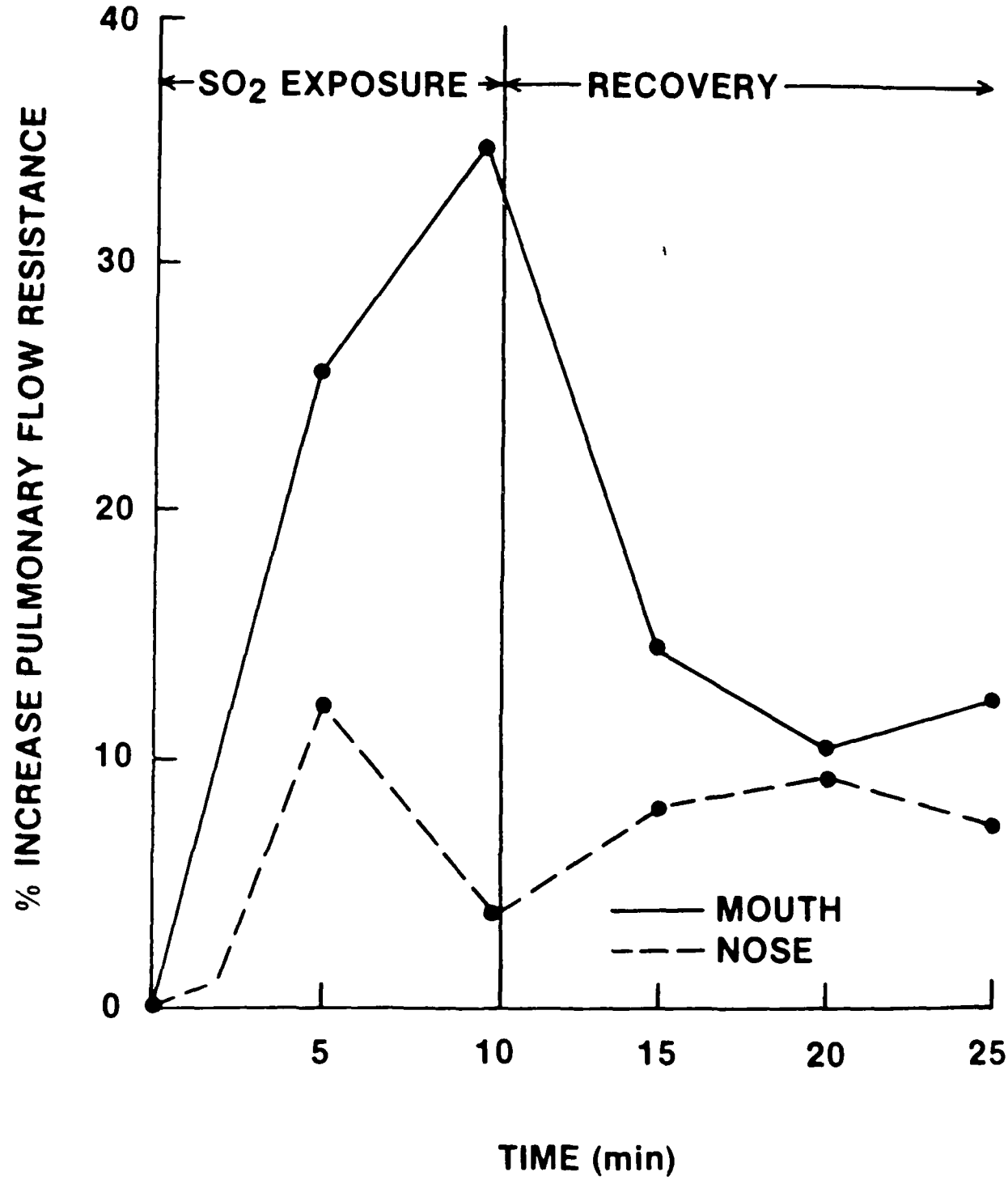
40
30
20
10
0
SO_2 EXPOSURE
RECOVERY
% INCREASE PULMONARY FLOW RESISTANCE
MOUTH
NOSE
5
10
15
20
25
TIME (min)

Fig.4

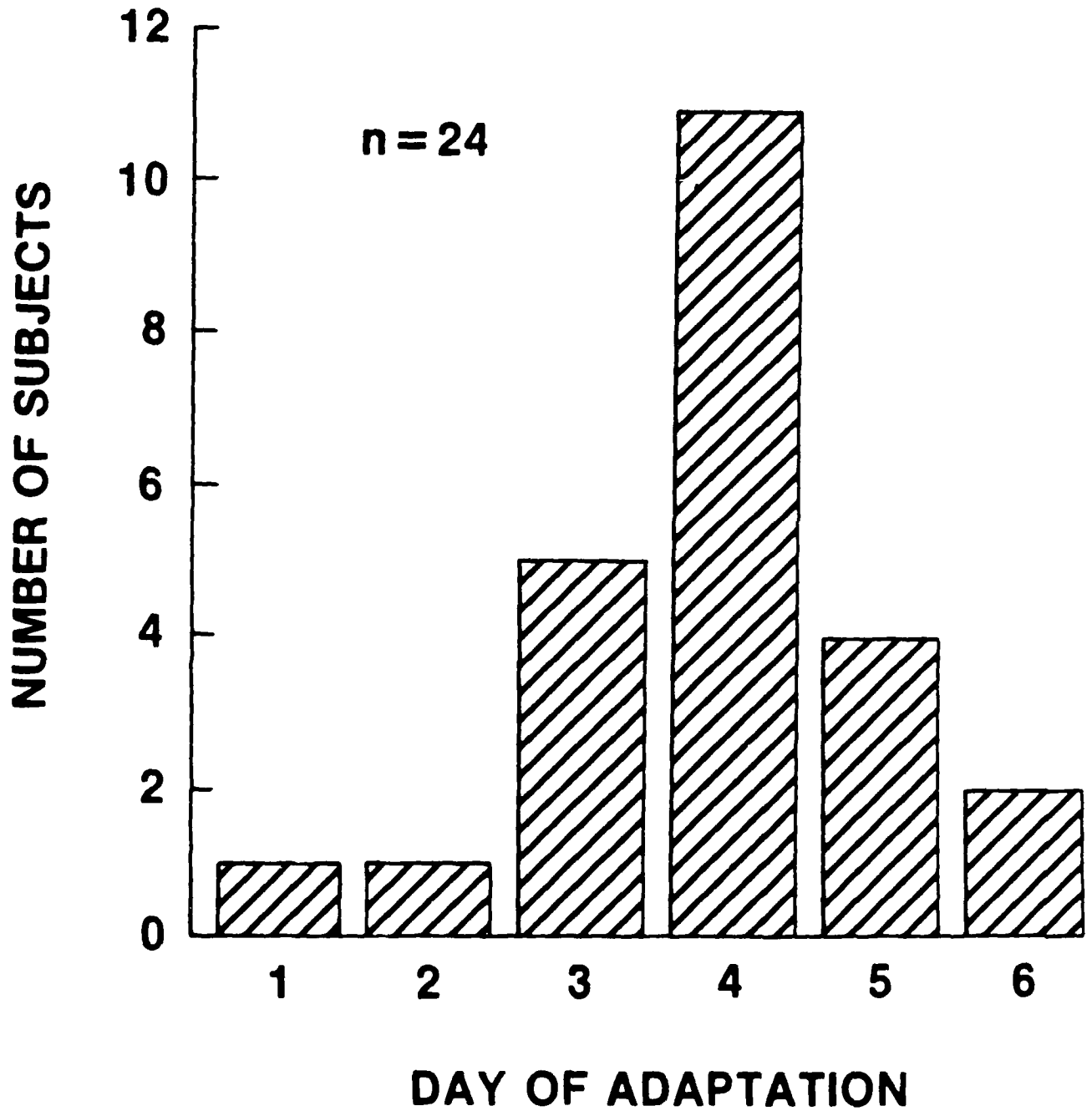

Fig. 5